Communication of uncertainties in radiological risk situations

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Foreword

I came to Belgium for the first time in 2017 to conduct my master studies at University of Antwerp. As an international student, I was applying for several different jobs, so that I could start working right after I would finish my master studies, and put in practice everything I’ve learnt so far. The rejection letters I was receiving one-after-another, however, really impacted my self-confidence as well as my mental health. Dark thoughts were taking over me, and I almost gave up everything,. But one day, my then master thesis supervisor (now PhD supervisor), **Prof. Peter Thijssen**, gave me a sparkle of hope. He told me that based on my master thesis, I would be a good candidate to apply for an open PhD position in collaboration between University of Antwerp and the Belgian Nuclear Research Centre (SCK CEN). Although I was informed that being the chosen candidate would not be an easy task, I still decided to go for it, and I got selected for this PhD project, whose main results you are about to read on this dissertation. **Peter**, thanks for seeing museums in me, when all I could see was empty walls. Furthermore, thanks for all the advise you have given me throughout this PhD journey. I know it wasn’t easy working with a student who “doesn’t take no for an answer”.

A special thanks goes to my PhD mentor **Dr. Tanja Perko.** Tanja, you already know you’ve been such a pain in the neck for me throughout this PhD journey, yet you’ve been the person I’ve admired and cherished the most. While I came to Belgium alone, without my family, you managed to very smoothly fulfill several roles for me. You were a mentor, when I needed PhD advice; you were a friend, when I needed life advice; you were a mother, when I needed someone to take care of me; and you are the best Godmother I could ever find for Reina. It’s not easy to find a mentor that is willing to babysit your child in the weekend so that her student can get some extra hours of sleep. You have always challenged and motivated me to never give up, no matter the circumstances. I keep learning so much from you, and you never fail to amaze me with your strength and wisdom.

Another important person in my PhD journey is **Prof. Ortwin Renn.** Dear Ortwin, I would like to sincerely thank you for everything you did to help me advance in my academic career, starting from always finding the time to provide me with constructive feedback, as well as to supporting my research stay at your institute in Potsdam. It has been an honor being your student.

In addition to Peter, Tanja and Ortwin, I would also like to thank the additional members of my PhD jury, **Prof. Dr. Heidi Vandebosch, Prof. Dr. Jeroen van der Sluijs, and Prof. Dr. Stefaan Walgrave**. Thanks a lot for guiding me throughout my PhD research, by providing advice in the annual PhD committee meetings, as well as discussing and providing feedback on the separate chapters of- as well as the full dissertation.

My gratitude also goes to the two research groups I was a member of throughout these four years. The **M2P** research group was the fun and cool group everyone would dream to be a member of. The M2P meetings and weekends were something I always looked forward to. Special thanks goes to my office (and the neighbouring office) mates: **Zeljko, Jeroen, Pieter, Michiel, Melisa, and Samira**. You were always ready to either help, or listen to my (plentiful) complaints. Especially **Melisa**, who even presented on my behalf in a research contest, while I was in the hospital taking care of my daughter.

The **NST** research group, on the other hand, was a more serious one, yet a very inspiring one. I would like to especially thank **Catrinel**, who was not only a great colleague for me, but also a great friend and gym-buddy. I'm so happy I met you as part of this PhD. **Joke** was the best office-mate I could ever ask for. You have seen me at my highs and at my lows. We've laughed out loud together, and you've also seen my ugly crying face. Thanks for always being a listening ear, for double-checking my Dutch e-mails, and for never hesitating to share your wisdom with me. **Stef**, thanks for helping me with the data issues I had with one of my articles, and always finding time to help me with Python. Additionally, I would like to thank all the **SPS** PhD students, for the fun PhD gatherings we had.

Blend, thanks for all the patience you've had and all the help you've given me since the moment we met each other. I can only imagine how difficult it was to leave your career, family and friendship in order to follow your wife so that she can complete her PhD. You are a perfect husband and father. *Faleminderit per durimin qe e ke pase dhe ndihmen qe ma ke bo prej momentit qe jemi njoftu. Nuk muj me imagjinu sa vshtire osht me e lon karrieren, familjen dhe shoqerine tonde per me ardhe te une deri sa ti kryj studimet e doktoratures. Je burre dhe baba perfekt.*

Mam, you are the reason I never give up. You motivate me to work everyday to acomplish my goals. You are the best example of a strong woman, an example I always try to follow.
Ti je arsyeja pse une nuk dorezohna kurre. Ti m'jep vullnet çdo dite me punu e me i arrite qellimet e mia. Je shembull i gruas se forte, shembull ky qe une mundohem me e ndjeke gjithmone.

Axhi Besim edhe Nani, thanks for always taking care of me as if I was your daughter. You are the second parents for me and the best grandparents ever for Reina.
Faleminderit qe gjithmone u kujdeset per mua sikur te isha vajza e juaj. Jeni prinderit e dyte per mua si dhe gjysherit me te mire ne bote per Reinen.

Lati, Eda, Arti, thanks for always being ready to help me in all aspects. You are the best gift our mom gave to me.
Faleminderit qe gjithmone jeni kone t'gatshem me m'ndihmu ne çdo aspect. Ju jeni dhurata ma e mire qe mami ma ka bo mu.

Reina, to be honest, you were not necessarily helpful throughout my PhD journey, on the contrary, you put quite some new and unforeseen challenges for me. Yet, you gave me purpose and joy in life. Only after I had you, I realized why I'm doing this PhD and what I want to accomplish with it. Only after I had you, I knew what real happiness is, and what is important in life. I now accomplished one of my main career goals. I hope my next career steps will be the right ones to pave a path for an easier and more beautiful life for you. Te dua mama's queen.

Finally, as Snoop Dog would say, I wanna thank **me**! The introduction of this thesis starts with "I am writing this thesis in times of a global energy crisis…". But actually I wrote this thesis in a much bigger personal crisis, due to some health issues of my daughter. Yet, I continued to show up at work, no matter how tired or how sick I was myself. I conducted studies while pregnant, I conducted studies amid Covid-19 waves, I conducted studies while my daughter was hospitalized. This is why I wanna thank me, for never giving up, and for juggling all the balls successfully, all by my own, while being far away from my family and the help they would normally offer.

Now, let's move to the content of the dissertation!

Abstract

In risk sciences, a great deal of progress has been made in terms of risk communication. Yet, findings on uncertainty communication, especially in the nuclear and radiological field remains scarce and contradictory. From the ethical, democratic, and transparency point of view, communicating uncertainties is essential since it not only provides all existing and missing information, but it also allows individuals to make informed decisions whether existing evidence is sufficient to justify certain actions. Given the complexity and the current controversy around nuclear energy, this dissertation studies uncertainties that are present in nuclear and/or radiological risk situations, and identifies the impacts that communication of such uncertainties has on emotions and participation intention of different target audiences such as laypeople and experts.

This dissertation aims at finding out 1) what types of uncertainties are there in nuclear and/or radiological risk situations; 2) What is the impact of uncertainty communication on participation intention; and 3) What is the impact of uncertainty communication on feelings and emotional arousal? The research questions of this dissertation were studied by using various methods such as scoping review of literature, non-participatory observation of nuclear/radiological emergency exercises, public opinion surveys, and psychophysiological experiment. In order to capture different aspects of nuclear/radiological risk situations, this dissertation focuses on two case studies: nuclear/radiological emergency situations, and decommissioning of nuclear installations.

Our research shows that different groups of society react differently to different uncertainties. When studied with the general population, communication of two out of three uncertainties (i.e. the amount of radioactive waste, and financial uncertainties) slightly negatively influenced self-assessed feelings of pessimism and worry. When tested with employees of nuclear-related institutions, one of the three uncertainties (i.e. public's acceptance of remaining radioactivity) did influence their emotional arousal, but none of the uncertainties influenced negative self-assessed feelings. Based on these results, this thesis concludes that while uncertainty communication might indeed cause some emotional effect on the short term, long term uncertainty information and familiarity with uncertainties will give assurance and comfortability with uncertainty information.

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Chapter 1: Introduction and research method

[…] The future is in many ways unknowable, and uncertainty is a basic condition of human knowledge and existence. This creates a paradox: How to provide certainty and security through knowledge of the future in the face of uncertainty as a basic condition of human knowledge?

Beck, 2009

Topic introduction, theoretical background and problem statement

I am writing the final parts of this thesis in times of a global energy crisis where geopolitical situations (i.e. Russian invasion of Ukraine) are influencing national decisions made about energy. Such decisions include price increase, investing more in renewable energy sources and/or new nuclear technologies such as Small Modular Reactors (SMRs), but also deciding on whether or not to delay phasing-out current Nuclear Power Plants (NPPs). Decision-making about energy in general, but especially about nuclear energy has always been complex (Hirose & McCauley, 2022). But the current situation with both, the Russian invasion of Ukraine, as well as the climate crisis only adds further to the complexity and decision-making under uncertainty. Such uncertainties go way beyond pure scientific uncertainties and can be, for instance, about the financial costs of extending the life of a nuclear installation or decommissioning it, security of the energy supply, safety of the nuclear reactors (e.g. nuclear accidents, terrorist attacks, proliferation), and public reactions towards decisions made. This is why, in this thesis, to define the term uncertainty I use a modified definition from Aven (2020: 5) which portrays uncertainty as *the potential deviations between unknown 'eventualities' and the related estimated, predicted, or assigned quantities and/or eventualities.* This definition allows for not only taking into account uncertainties that result from measured (estimated, predicted) quantities, but also unmeasured, perceived, and assumed (assigned) quantities, eventualities and/or situations, thereby including all various dimensions of uncertainties.

In the recent years, in several fields (e.g. medicine, natural hazards, food safety) there is a growing recognition of the broader social aspects of uncertainties, including their *communication* (between actors in the scientific community, from scientific community towards other actors such as decision-makers, media and laypeople, or from lay people towards decision-makers or scientists) (Doyle, McClure, Paton, et al., 2014a; Hart et al., 2019; Jensen et al., 2016; Maxim, 2014; Van Der Bles et al., 2019). Yet, the nuclear field remains an understudied field when it comes to this aspect. What makes the nuclear field a peculiar topic to be studied when it comes to uncertainties and their communication is the complex nature of such high risk, high gain technology, which is accompanied by many different uncertainties, and where decisions have to be made carefully given that they can have a major impact on people's lives, health, and the environment (IAEA, 2011; Taebi, 2012). This is why, in this thesis I study the impacts of communication of uncertainties that are present in nuclear and radiological situations, and decision-making under them. In order to capture different aspects of the nuclear and radiological field (e.g. safety, security, public reactions, technical and financial aspects of operating nuclear installations and of those that are shutting down), I selected two cases to study: nuclear/radiological emergency situations, and decommissioning of nuclear installations.

While uncertainty is present in all fields and disciplines, communication of uncertainties still remains a challenge. In a period of "posttruth" (Keyes, 2018), "culture of fear" (Furedi, 2002), and "merchants of doubt" (Oreskes & Conway, 2010) we are living nowadays, where scientific results and facts are increasingly contested and casted doubt upon, and people are ever more uncertainty averse, a common assumption is that communicating uncertainty will reduce public trust, and cause even more fear and anxiety (Doyle, McClure, Johnston, et al., 2014; Han et al., 2010; Maxim et al., 2013; Van Der Bles et al., 2019). Yet, from the ethical, democratic, and transparency point of view, communicating uncertainties is essential since it not only provides all existing and missing information, but it also allows individuals to make informed decisions whether existing evidence is sufficient to justify certain individual and collective actions (Funtowicz & Ravetz, 1993; Han, 2012). In addition, when uncertainties are not communicated timely and are later revealed by other sources, one can observe a significant loss of credibility in the original communicator (Perko, Benighaus, et al., 2020a). The accusation that important information was withheld from the public can lead to a decline of trust and reputation. When it comes to the importance placed in transparency, public opinions, trust, perceptions, and feelings, the case of nuclear and radiological field makes an ideal case selection. This is why, testing the impacts of uncertainty communication on feelings, emotional arousal, and public participation intention in this field not only contributes to the missing literature on uncertainty communication in the nuclear and radiological field specifically, but also offers empirical findings in order to resolve the contradictory findings about the impact of uncertainty communication on feelings and emotions in general.

Theoretically, this thesis is primarily inspired by the Post-Normal Science (PNS) paradigm, which is an approach for the use of science on issues where "facts [are] uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz & Ravetz, 1997: 169), which fits with the case selection of this thesis. The PNS paradigm has three key elements: 1) the management of uncertainty (taking into account not only technical and methodological uncertainties, but also uncertainties that arise from epistemological, societal and ambiguous nature); 2) the management of the plurality of perspectives within and without science (emphasis on inter-and transdisciplinary efforts from various areas such as science, business, politics, and society); and 3) the extension of the peer community (including representatives from social, political, and economic domains to discuss different dimensions and implications of decisions, and in addition for reliability and validity, to also test for “social robustness”) (Petersen et al., 2011; Ravetz & Funtowicz, 2015). This points to the relevance of public participation in complex decision-making procedures, which, aside from feelings and emotional arousal, is the ultimate dependent variable in this thesis. While according to the PNS paradigm, uncertainty communication and stakeholder and public involvement go hand-in-hand (Petersen et al., 2011), and the more uncertainty there is, the more public participation is needed (Renn, 2015), the relationship between the two has so far not been empirically tested. This thesis thus further contributes to the missing literature on this aspect by testing the impact of uncertainty communication on public participation in decision-making procedures directly, and indirectly, through feelings and emotional arousal.

In sum, by focusing on nuclear/radiological emergencies and decommissioning of nuclear installations as two case studies, and by being inspired by the PNS paradigm, this thesis aims to answer the following research questions: *What kind of uncertainties exist in nuclear and radiological situations? What is the impact of uncertainty communication on participation intention in nuclear-related decision-making procedures? What is the impact of uncertainty communication on feelings and emotional arousal of information receivers?*

To answer these research questions I have conducted five empirical studies (see figure 1), focusing on first identifying uncertainties present in literature, then identifying different uncertainties present in the nuclear/radiological emergencies, and afterwards on testing the impact that uncertainty communication has on feelings, emotional arousal, and public participation intention related to decommissioning of nuclear installations. To do so, this thesis uses a multidisciplinary approach and it adapts and synthesizes concepts and theoretical models stemming from a number of fields such as: Cognitive Functional Model (Nabi, 1999), Uncertainty Reduction Theory (Berger, 1986; Bradac, 2001), Uncertainty Management Theory (Brashers, 2001)); Affective Intelligence Theory (Marcus et al., 2002); Value-Belief-Norm Theory (Stern et al., 1999) and Arnstein's ladder of participation (Arnstein, 1969).

In the following sections I provide explanations of the various terms used in this thesis, as well as the theoretical arguments behind the choice to use these terms and variables in this thesis. What follows is the case selection, research methodology, as well as the outline of the thesis.

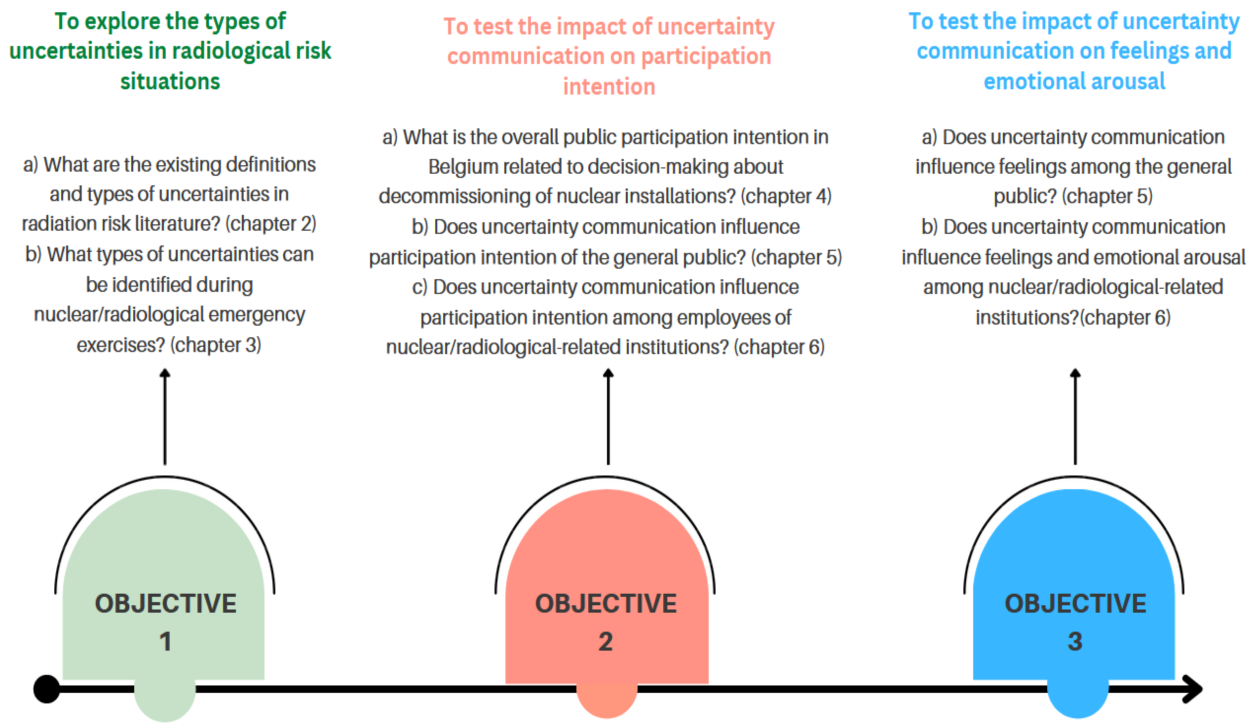

Figure 1. Objectives and research questions of the thesis, addressed across six chapters.

Conceptual framework and state-of-the-art.

Uncertainty definition

Although there is not much research on the impact that uncertainty communication can have on feelings and public participation in nuclear and/or radiological-related issues, the issue of uncertainty in general has been extensively studied in literature. Van Asselt (2000) explains how starting from the 18th century, during the Enlightenment period, there was already a separation of true and certain knowledge which could be achieved by following strict mathematical and quantitative methods on the one hand, and boundaries beyond which human understanding could not venture, on the other. Later on, in the 20th century, Knight (1921) made an important distinction between risk, in which there is agreed quantification due to extensive data, and uncertainty, which is not susceptible to quantitative measurement (Knight, 1921; Spiegelhalter, 2017a). In mid-20th century, proponents of post-modernism were arguing that the search for certainty is an illusion (Bell, 2009), whereas social constructivism posed that the criteria to distinguish between valid and invalid scientific statements are socially constructed and can therefore not be derived by pure reasoning (Rathbun, 2007; van Asselt, 2000). In the late 20th, and especially in the 21st century, a much bigger and more dedicated focus of uncertainty has been devoted by several scholars in different disciplines, taking into account not only uncertainty measurement, but also its communication and interpretation. The notion of uncertainty expanded from purely cognitive uncertainty (lack of/insufficient/ambiguous information) towards other types such as normative uncertainty (values, judgements, perceptions) (Renn, 2008b).

At current state, there are different definitions of uncertainty in the literature (for a detailed summary, see chapter 2). These definitions differ based on factors such as the nature/source of uncertainty, its level, location (Hart et al., 2019; Walker et al., 2003), and the actor(s) facing and/or expressing the uncertainty (Maxim et al., 2013).

The *nature* of uncertainty indicates the source where the uncertainty is coming from, namely, whether it is due to the limitations of our knowledge or is due to the intrinsic variability of the phenomena being described (Walker et al., 2003). The main three distinctions in this respect are between epistemic, aleatory and ambiguity-related uncertainties. Epistemic uncertainties refer to limitations in knowledge, and can thus be decreased with more information and/or knowledge (Doyle, McClure, Paton, et al., 2014a; Eiser et al., 2012a; Fearnley, 2013). Sources of epistemic uncertainties include inexactness, and lack of observations/measurements, conflicting evidence, lack of knowledge about context conditions, etcetera (Funtowicz & Ravetz, 1990; van Asselt, 2000; Walker et al., 2010; Wynne, 1992). Aleatory uncertainty, on the other hand, is stochastic and of random nature, and can thus not be reduced (Eiser et al., 2012a; Knoblauch et al., 2018; Kox et al., 2015). Sources of aleatory uncertainty include natural randomness, behavioral variability, social randomness, the occurrence of unexpected surprises (Funtowicz & Ravetz, 1990;

Rowe, 1993; van Asselt, 2000). Additionally, ambiguity refers to value diversity in evaluating and interpreting evidence, vagueness or situations that can be interpreted in multiple ways depending on the context. It allows for space to interpret knowledge in different ways or draw different normative conclusions from an identical set of evidence (Kox et al., 2015; Markon et al., 2013; Renn, 2008b; Romao & Pauperio, 2016).

The *level* of uncertainty indicates a range from what is known, towards what is unknown. Walker et al. (2003: 11) refer to this spectrum as "ranging from the unachievable ideal of complete deterministic understanding at one end of the scale to total ignorance at the other". At the side of deterministic unknowns are, for instance, statistical uncertainties, scenario uncertainties, and then on the other side of the spectrum we have recognized ignorance, and total ignorance. In a similar line of thought, one year earlier, Rumsfeld defined uncertainty based on "known unknowns, and unknown unknowns" (Rumsfeld, 2002).

The *location* of uncertainty refers to where uncertainty manifests itself in a certain situation (Walker et al., 2003, 2010). It can appear as, for instance, a component in the risk assessment (Hart et al., 2019), as context uncertainty (in the problem framing stage) (Walker et al., 2003), model uncertainty (e.g. parameter estimates and exposure scenarios) (Oberg & Bergback, 2005), input uncertainties (when external forces drive changes to a certain system) (Walker et al., 2010), as well as communication uncertainty which arises communication includes contested evidence (competing knowledge claims) and the parallel communication of factual and fake news (Maxim, 2014; Tomkiv et al., 2020).

Finally, uncertainty definition also depends based on the type of *actor* that is facing and/or expressing a certain uncertainty. For instance, a scientific message transforms when it is communicated from the information provider towards information receivers (Maxim et al., 2013). Recent studies show that there are differences between uncertainties that scientists are faced with in comparison to the uncertainties of the public (Maxim & van der Sluijs, 2011; Tomkiv et al., 2020). This is why in some instances uncertainty is expressed as an object of knowledge, whereas in other situations it is mentioned as an experience, perception, or a feeling (Abbott et al., 2006; Blanchemanche et al., 2010; Maxim et al., 2013; Slovic et al., 2004).

Given that the definition of uncertainty is influenced by so many factors, in this thesis, I use the term uncertainty in a broader sense, which incorporates these many different dimensions of uncertainty, in order to bridge the gap between various concepts across different actors and research fields (SHARE, 2020). In the next sub-section I explain what uncertainty communication means and why I chose three specific types of uncertainties for testing the impacts of uncertainty communication.

Uncertainty communication

Uncertainty communication is a process of communicating information about uncertainty a) between actors in the scientific community; b) top-down: from the scientific community towards other actors (e.g. decision-makers, media and laypeople); and c) bottom-up uncertainty communication (from laypeople towards decision-makers and/or scientists) (Harris, 2015).

Uncertainties can be reported in verbal, numeric, graphical or digital/visual form (Van Der Bles et al., 2019). Combination of several methods is recommended since it is designed to improve the understanding of the message and targets different ways, channels, formats of communication (Doyle, McClure, Johnston, et al., 2014; Knoblauch et al., 2018; Perko, Benighaus, et al., 2020a; Spiegelhalter, 2017b; Wardekker et al., 2008; Wolf et al., 2020).

Literature on uncertainty communication has mainly focused on testing top-down uncertainty communication, namely from scientists towards decision-makers, media, or laypeople (Babrow, 2001; Hart et al., 2019; Jensen et al., 2016, 2011; Spiegelhalter, 2017b). Research on bottom up uncertainty communication (Maxim et al., 2013; Powell et al., 2007; Retzbach et al., 2016), especially in the nuclear field (Perko, Benighaus, et al., 2020a) remains scarce. To address this, in this thesis I focus on a combination of top-down uncertainty communication, with bottom-up communication and participation intention. For the former, I test the impact of communication of experts' uncertainties. For the latter, as a dependent variable I use public participation intention in decision-making procedures, which is a way for the members of the public to express their knowledge, expertise, opinions, concerns, and give their general contribution to decision-making procedures (De Marchi & Ravetz, 2001; Krütli et al., 2010). Combining these two approaches is important because the field of risk communication has evolved from "All we have to do is get the numbers right," "All we have to do is tell them the numbers," and "All we have to do is explain what we mean by the numbers" towards "All we have to do is make them partners" (Fischhoff, 1995: 138). This combination thus allows for testing not only how the public perceives uncertainty communication, but also whether or not they prefer uncertainties to be communicated at all, the impact that uncertainty communication has on their feelings and emotions, as well as whether they are willing to participate in decision-making procedures based on the uncertainty information that they get.

Decision-making about-, under-, and because of uncertainty

Uncertainty can have various impacts such as scientific (e.g. the accuracy of scientific results), societal (e.g. feelings, emotions, trust), political (e.g. how to make decisions when there is lack-of, insufficient, or contradictory information), and ethical (e.g. what recommendations to give to the affected population based on incomplete information), among others. Thus, the need to decide about uncertainty (whether or not to act, how to act, whether or not to communicate about uncertainties, how to communicate) arises (van Asselt, 2000; van der Sluijs, 2005). One of the main rationales of effectively communicating *about* uncertainty is to help the receivers of the information make informed judgments and decisions to achieve the long- as well as short-term goals (Doyle, McClure, Johnston, et al., 2014; Fischhoff & Davis, 2014).

Very often, decision-makers need to make decisions *under* of uncertainty (Greenberg et al., 2019; Van 't Klooster & Veenman, 2021). Decision-making in the face of uncertainty is a process of choosing among various options for taking action (including doing nothing), in situations where there is contradictory, ambiguous, imprecise or no information at all (Renn, 2008b). At times, such decisions are well-thought of, careful and resulting from analytic, deliberative conversations (K. E. Anthony & Sellnow, 2016). Other times, especially in urgent situations that need quick reactions, decision-makers are prone to use heuristics and to make systematic errors (i.e. representativeness, availability and anchoring biases) (Kahneman & Tversky, 1974; Renn et al., 2021). Analyzing how different actors such as decision-makers, emergency managers, first responders, communication officers and laypeople make decisions under uncertainty in the nuclear field is of thus of crucial importance. The second chapter of this thesis focuses specifically on this matter, taking nuclear emergency exercises as a case study.

Sometimes decisions are also made *because* of uncertainty. As human beings, very often, we are trying to reduce uncertainty (Bradac, 2001). When encountering uncertainty, people are more likely to be involved in verbal conversations or information-seeking behavior, especially when they believe that such behavior will lead to less uncertainty (K. E. Anthony & Sellnow, 2016; Nabi, 2002). In other instances, uncertainties are managed, amplified, attenuated, and/or manufactured when making decisions (U. Beck, 2009; Brashers, 2001; Kasperson et al., 2022; van der Sluijs, 2005). For instance, when uncertainty is perceived as posing a threat to an individual, they are willing to reduce it. However, when people see it as an opportunity not to act on it, they are like to strategically frame it in order to support their (lack of) actions. For instance, lack of scientific agreement and available instruments to measure the risk of climate change has been found to influence lower concern about climate change among citizens, which in turn would lead to them not adopting climate-mitigation measures (Visschers, 2018). Another example of making decisions because of uncertainty is the (potential) nuclear energy comeback in many countries due to the energy crisis as a consequence of the international sanctions towards Russia after its invasion of Ukraine (Euractiv, 2022a; Politico, 2022). Such uncertainties are what Beck (2009: 291) calls "manufactured uncertainties" – uncertainties that are dependent on human decisions, created by society itself, collectively imposed, and thus individually unavoidable. This points to the relevance of testing how different actors react, and decide because of the uncertainty they are communicated about. In chapter five and six I test this by testing whether uncertainty communication increases experts' and public's participation intention. More specifically, I test whether, when receiving information about uncertainties, participants in the study are willing to participate in decision-making procedures about decommissioning of nuclear installations, in order to either receive more information, express their opinion, participate in dialogues, or being partners in decision-making (Hoti, Perko, & Turcanu, 2021). In the next section I explain in more detail what public participation means, which forms of public participation exist, and how we test it.

Public participation intention

Decision-making about complex environmental and technological matters demands careful consideration of various requirements. On the one hand, sufficient knowledge about potential impacts of the risks, benefits, consequences, and uncertainties under investigation of a certain decision is required to produce evidence-based decisions. On the other hand, decision-makers and risk managers also need criteria for judging the acceptance or unacceptance of such consequences for the people affected and the public at large (Renn, 2008b). Since uncertainties are an inherent part of risk management, and they affect different parts of the populations to various extents, it is of crucial importance that the decision-making processes integrate the knowledge, expertise, values, interests, and concerns of different stakeholders (Bergmans et al., 2015; Bond et al., 2004; Hage & Leroy, 2008; Pellizzoni, 2003; Renn, 2015). Furthermore, because of the importance of multi-way communication, and the integration of different forms of knowledge, public participation in decision-making procedures is considered a hallmark of risk communication (National Academy of Sciences, 2013; Renn, 2008b). Public participation means the inclusion of citizens in the activities of any organization or project. Its aim is to provide citizens with the opportunity of learning about the technical and political facets of decision-making options and enabling them to discuss and evaluate these options and their likely consequences according to their own set of values and preferences (Renn, 2008b). Some of participation procedures are, but are not limited to, referenda, public hearings/consultations, focus groups, public opinion surveys, negotiated rule-making, consensus conferences, citizen jury/panels, citizen advisory committees (HIS Community Engagement, 2022; Renn, 2008b).

Public participation in decision-making procedures is recommended by several European regulations such as the amended Environmental Assessment Directive (2014/52/EU) and European Council Directive (2011/92/EU), as well as by several scholars (Hage & Leroy, 2008; Invernizzi et al., 2017, 2020; Krütli et al., 2010; Liu et al., 2020, 2021; Pellizzoni, 2003; Perlaviciute, 2022; Renn, 2015; Turcanu et al., 2014). Additionally, empowering citizens in environmental matters is also a goal of the Aarhus Convention (United Nations, 1998, 2014), which requires from the signing members to provide the public access to environmental information *(the right to know),* to participate in the decision-making process *(the right to participate),* and to have access to justice *(the right to a healthy environment)* (United Nations, 1998). Belgium, the case study of this thesis is one of the signing countries of this convention, and because *decommissioning of nuclear installations can affect people in different dimensions (health, financial, jobs, environment, future generations), it is a fitting example of an environmental matter about which the public has to be informed about, consulted with, and involved in*. This is why, in this thesis, starting from chapter four onwards, I focus on decommissioning of nuclear installations in Belgium, the extent to which Belgian citizens are willing to participate in decision-making procedures about it, and whether or not uncertainty communication influences this participation intention.

Why would we want/care to participate? There are different goals for public participation. Apart from the *normative* aspect that decisions have to be legitimate in the democratic societies we live in (Hage & Leroy, 2008), there is also a *substantive* rationale, which means that relevant wisdom is not limited to technical experts, but everyone can contribute to an effective and fair decision-making process when inserting experiential, local and tacit knowledge (Wesselink et al., 2011). Transdisciplinarity in which co-creation of knowledge with different actors is desirable and necessary for complex issues (Hage & Leroy, 2008;

Pohl, 2010). Public participation also has an *instrumental* rationale. It has been found that decision-making panels that comprise of both, experts and citizens (in comparison to panels with only experts, or only citizens) were evaluated as having more expertise and more capable to take high quality decisions, thus leading to more support for the solutions and/or policies chosen (Liu et al., 2021). To sum, public participation in decision-making procedures allows for inclusion of more, and various perspectives, opens up for a wider range of (policy) options, assists in avoiding type III errors (addressing "wrong" problems), and reduces the likelihood of unforeseen impacts of policies/solutions chosen by extending the peer community from only scientific, towards political, social and economic domains (Hage & Leroy, 2008; Pellizzoni, 2003; Petersen et al., 2011; Wesselink et al., 2011).

While there are many arguments of why public participation is of mutual benefit, for both, decision-makers and society, we have to keep in mind that it is also a very costly and time-consuming procedure. This is why it is important to apply the correct level and form of participation, depending on the complexity of the issue (Hage & Leroy, 2008). In certain issues, the cognitive dimension (informing policies and co-creation of knowledge) suffices (Pellizzoni, 2003), in other situations co-deciding is necessary or even legally required (Hage & Leroy, 2008). In situations where large degrees of uncertainty are present, public participation is an appropriate tool to gather and make use of pluralistic perspectives for better decision-making (Hage & Leroy, 2008; Pellizzoni, 2003; Renn, 2008b). Members of the public can participate based on different roles and capacities such as laypeople, affected population, knowledge-holder, stake-holder, right-holder, and quality-control (Hage & Leroy, 2008).

In this thesis, I test the willingness of Belgian citizens to participate. To do so, I use a scale which is based on Arnstein's ladder of participation (Arnstein, 1969). This ladder involves different levels of participation, starting from no participation, to informing, studying, listening, consulting, taking advise, co-producing, and finally co-deciding, where citizens have equal opportunities in decision-making committees (Arnstein, 1969). In addition to testing our respondents' willingness to participate, I also test whether uncertainty communication influences this intention or not. Renn (2015) argues that in situations accompanied by uncertainty, the type of decision-making needs to be reflective in the sense that it should involve all affected stakeholders in order to decide on the best compromise between too much and too little precaution. Existing theories of communication and decision-making under uncertain situations argue that communication of specific messages will influence information processing and subsequent attitude change (Bradac, 2001; Brashers, 2001; Marcus et al., 2002; Nabi, 1999). When encountered or provided with uncertain information, individuals are more likely to seek reassurance, and will therefore either seek additional information or engage in decision-making procedures to find out if such reassurances will be achieved (Nabi, 1999, 2002). Thus, individuals that believe that their actions will lead to less uncertainty, and that their actions can have an impact in the decision-making procedure, are more likely to participate (Marcus et al., 2002, 2011; Van ’t Klooster & Veenman, 2021). In addition to this, we know from existing research on perceived level of knowledge that participants that perceive themselves as knowledgeable or experienced with a certain topic, are more likely to participate (Hibbing & Theiss-Morse, 2002; Muhlberger, 2018; Pellizzoni, 2003; Reichert, 2016). Decommissioning of nuclear installations is an issue about which the majority of the public does not have a lot of information and/or knowledge about (Hoti, Perko, & Turcanu, 2021), and thus does not feel competent enough to participate. This is why I hypothesize that telling them that even experts themselves are encountered with uncertainties about decommissioning, might increase their participation intention (tested in chapter five and six).

Feelings and emotional arousal

Public participation intention is found to be influenced by feelings and/or emotions generated by the issue at stake (Brashers, 2001; Marcus et al., 2002; Nabi, 1999). In this section, thus, I present with the state-of-the-art findings in the topic of feelings and emotions when it comes to public participation. Furthermore, I explain what the concept of feelings, emotions, and emotional arousal means in this thesis.

The division and/or interlinkage between emotional and rational decision-making has preoccupied scholars for a long time (Fischhoff et al., 1978; Gigerenzer, 2007; Gigerenzer & Todd, 1999; Haidt, 2001; Nabi, 1999; Slovic, 1992; Slovic et al., 2004; Tversky & Kahneman, 1986). Theoretical models such as the Elaboration Likelihood Model (ELM) (Petty & Cacioppo, 1986), the Heuristic-Systematic-Model (HSM) (Chaiken, 1980), and the Prospect Theory (Tversky & Kahneman, 1992) are among the several prevalent models that have been developed to explain how information-processing, persuasion and decision-making under uncertainty works among individuals. However, these models touch only indirectly upon the topic of emotions and/or feelings. For instance, the Elaboration Likelihood Model argues that there are two different routes of persuasion (central and peripheral route). Persuasion is achieved via the central route when the receiver examines each argument carefully and balances the pros and cons in order to form judgement. The peripheral route, on the other hand refers to a faster and less careful strategy (Petty & Cacioppo, 1986). Updated versions of the ELM, however stress that emotions can influence the extent, direction, and the thoughts that come up in the information-processing activity by serving as a peripheral cue (Cacioppo & Haugtvedt, 1987; Morris et al., 2005; Petty et al., 1991). Similarly, the HSM also argues that people make decisions based on two different systems. According to Chaiken (1980), people are expected to base decisions on heuristics, should those heuristics allow them sufficient confidence in the accuracy of their judgments. If not, then they will also engage in the more effortful systematic processing (Chaiken, 1980; Nabi, 1999). Finally, the prospect theory, argues that people make decisions based on options that are themselves based on biased judgements (Tversky & Kahneman, 1992). In context of the prospect theory, the potential effects of emotion are relevant for the subjective evaluation of utility or value, weighing different decision options, and framing of prospects as a gains or losses (Prietzel, 2020). Affect heuristic is one example of how people make decisions based on emotions, rather than concrete information (Kahneman, 2011; Slovic & Peters, 2006).

More recent work on judgement and decision-making, especially decision-making under uncertainty argues that emotion and reason are complementary to each other, and cannot (and need not) be separated (Gigerenzer, 2007; Nabi, 2002; Slovic et al., 2004; Todd & Gigerenzer, 2000). Moreover, "analytical reasoning cannot be effective unless it is guided by affect" (Slovic et al., 2004: 311). The nuclear field is a clear example of how difficult it is to distinguish emotional and rational behavior. For instance, when told not to use phones during a nuclear emergency, should parents that nevertheless use it to call their children/family be considered as rational (for consciously taking care of- and informing other individuals) or emotional (for letting their emotions interfere with professional advice)? What about protesting against storing radioactive waste in the vicinity of the protesters? Additionally, is the decision to prolong the activity of nuclear power plants a rational decision amid the current energy crisis, or is it an emotional one in the form of fear and solidarity concerning energy security?

Given that emotions play such an important role in information-processing, attitudes, behavior, and decision-making, this thesis looks at the role of feelings and emotional arousal on information seeking behavior and participation intention in decision-making procedures about decommissioning of nuclear installations. Yet, while emotions can be an important predictor of our variables of interest, they themselves can be influenced by several factors too. Uncertainty communication is one of the factors that is found to influence emotions (Jensen et al., 2016; Nabi, 2002; Van Der Bles et al., 2019). For this reason, this thesis looks at the role of feelings and emotional arousal as mediating variables.

There are several theories that support the mediating role of feelings and emotions between uncertainty communication and public participation intention. Some of these theories, which this thesis is also based on, are Uncertainty Management Theory (UMT) (Brashers, 2001), Cognitive Functional Model (CFM) (Nabi, 1999), and Affective Intelligence Theory (AIT) (Marcus et al., 2002). According to UMT, people judge the meaning of an event, as well as their reaction towards this event based on the impact it has on their emotions and the relevance it has to their lives (Brashers et al., 2002). For instance, when uncertainty is perceived as threatening one's health and safety, it can cause anxiety and

worry. In other situations, uncertainty can result in a positive emotional response if it raises feelings of hope or optimism (Brashers, 2001). Both ways, such emotional reaction to uncertainty influences individuals behavioral intentions (Brashers, 2001). Similar arguments are raised by AIT too. According to this theory, people have two separate emotional systems leading to two different decision-making strategies: the disposition system, and the surveillance system. The former involves feelings like enthusiasm and aversion, and thus leads people to rely on existing habits. The latter, however, involves feelings such as anxiety and thus activates in novel and/or threatening situations. When decisions are made as part of the surveillance system, people are more likely to seek more information and participate in decision-making procedures (Marcus et al., 2002; Vasilopoulos, 2019). Similar to these two theories, CFM focuses on the various impacts of feelings when it comes to their effects on engagement with information and their avoidance or approach-based response (Nabi, 1999). This theory argues that negative emotions such as anger increase motivation to
approach or engage with the message and the source of information that is influencing their feelings, regardless whether their expectation of information reassurance is certain or uncertain (Nabi, 2002). On the other hand, those participants experiencing emotions such as fear or worry will refrain from engaging because fear makes individuals ‘shrink from action’ and cause lack of control (Karl, 2021: 693). However, if there is uncertainty about the fear or worry-inducing message, and the person facing these feelings believes that getting more information and/or being engaged in a decision-making procedure will bring additional information to satisfy/address their emotions, then motivation to engage with the affect’s source is increased (Nabi, 1999, 2002).

Finally, it is important to explain the difference between emotions, feelings, and emotional arousal. Emotions are the primitive, fast, and unconscious mechanisms responsible for our responses to various situations, whereas feelings are those conscious and cognitive perceptions we use to describe our emotions (Hansen, 2005). Emotions can be described based on valence (the extent to which an emotion is positive or negative) and arousal (the intensity of the emotion). More specifically, emotional arousal refers to the psychological state and the intensity of being roused due to a stimulation in the environment (Howell et al., 2019). By measuring activation levels of the sympathetic nervous systems (such as heart rate, blood pressure, respiration rate, muscle tension, and skin temperature), it can influence participants' interpretation of the stimuli, and potentially also their reaction towards it (Ouvrein et al., 2020). Existing research on emotions shows that negative stimuli generally generate higher arousal than positive stimuli (Citron et al., 2014). Given that one of the goals of this dissertation is to analyze the impact of uncertainty communication on feelings, as well as the intensity of the emotional experience with respect to the stimuli of the dissertation experiments, I mainly focus on feelings and emotional arousal, when analyzing the mediating effect of these two variables. Combining the measurement of self-reported feelings and emotional arousal is an added value since neural activity can predict variability in behavior change that is not predicted by subjective measures (Falk et al., 2011), and at the same time subjective measures can help in interpreting the meaning of emotional arousal levels.

Case selection

The Belgian context

The nuclear and radiological field have received ample attention from social science research, especially after the Three Mile Island, Chernobyl, and more recently the Fukushima accident (e.g. Abbott et al., 2006; Bernardi et al., 2018; Brown, 2019; Perko et al., 2019). Belgium has been mainly used as a case study in research focused on the political aspects of nuclear energy (Latré et al., 2019; Müller & Thurner, 2017), media reporting of the nuclear/radiological aspects (Perko, Prezelj, et al., 2019; Perko & Martell, 2020; Prezelj et al., 2016), as well as stakeholder engagement/participation aspects (Invernizzi et al., 2017; Perko, Martell, et al., 2020; Turcanu et al., 2014). However, when it comes to uncertainty communication, decision-making under uncertainty, and public participation intention about decommissioning of nuclear installations, Belgium remains an understudied case. What makes Belgium a relevant case study in this respect is the fact that it currently relies in nuclear energy for about half of its electricity production (World Nuclear Association, 2022). Initially, Belgium planned to close all of its NPPs by year 2025. While as part of this plan, in September 2022, the first Belgian power reactor (Doel 3) shut down after 40 years of operation, Belgium still decided to extend the lifetime of its last two NPPs (Doel 4 and Tihange 3) by 10 years, due to the current geopolitical situation and the energy crisis (Euractiv, 2022a). This makes this country a relevant case study for both, nuclear/radiological emergency situations (for both, the operating nuclear installations, and the ones that are shut down), as well as decommissioning of nuclear installations (for the reactors that are shut down and will undergo the decommissioning process).

Furthermore, in this dissertation I used multiple methods, and different types of respondents, which make the findings of the results generalizable to various populations. Finally, the uncertainties that I identified and tested in the studies related to nuclear/radiological emergencies, and decommissioning of nuclear installations, appear to be similar in various countries (Hirose & McCauley, 2022; Hoti, Perko, Tafili, et al., 2021). This makes the results of the findings of this dissertation applicable to other democratic countries as well. In the following two subsections, I explain the two case studies and the uncertainties they are accompanied with.

Decommissioning of nuclear installations

Nuclear installations must be decommissioned after they finish their operational lifetime. This process involves dismantling of the installation and the infrastructure, the remediation and clearance of the buildings, and the demolition of these buildings. Given the ageing of the nuclear installations that were built worldwide during the nuclear renaissance, they are being and/or have to be decommissioned soon (Goodfellow et al., 2011). Yet, the decommissioning processes of these installations are being delayed due to various uncertainties (e.g. geopolitical situation and energy crisis caused by the Russian invasion of Ukraine). This makes decommissioning of nuclear installations, and the uncertainties related to it of crucial importance to be studied.

Apart from the geopolitical situation, decommissioning of nuclear installations involves many other uncertainties, which go way beyond the technical, measurement, and scientific uncertainties. Uncertainties about the public reactions towards the decisions made can be an example. For instance, on the 23rd of September, 2022, the first Belgian power reactor shut down (reactor 3 of Doel NPP) after 40 years of operation. Because this decision was implemented during the energy crisis, hundreds of citizens were protesting, and together with several non-profit organizations, plan to sue the Belgian state (Euractiv, 2022b) for deciding to shut down its reactors amid uncertainties of energy supply security and price instability. On the other hand, the German government made the opposite decision by deciding to keep its last two NPPs (Isar 2 and Neckarwestheim 2) running up until mid-April 2023, in order to have a back-up for its energy supply. Still, this decision sparked dissatisfactions and criticism among several political parties as well as members of the public (Politico, 2022) who mainly bring up uncertainties concerning the safety of nuclear installations.

Other uncertainties related to decommissioning involve, but are not limited to, uncertainties about the duration of the decommissioning process; about the financial costs; potential loss of income for the local communities; potential loss of jobs, expertise, and knowledge; limited existing experience with previous decommissioning projects; different types and designs of reactors; security-related uncertainties (e.g. terrorist attacks, nuclear fuel transport, etcetera), the amount of radioactive waste produced; behavior of employees and contractors (e.g. one study in UK found that contractors were doing shortcuts which was then causing additional problems (Hirose & McCauley, 2022)); intergenerational impacts (e.g. the reactors were designed by another generation, were operated and decommissioned by other generations, and the process will last many decades, being passed to future generations); environmental impacts; and lack/loss of plans and drawings (Hirose & McCauley, 2022; Invernizzi et al., 2017, 2020; Martell & Perko, 2022).

In this dissertation, when testing the impacts of decommissioning-related uncertainty communication, I use three types of uncertainties which appeared to be crucial based on existing literature as well as discussions with decommissioning experts. These uncertainties are: 1) uncertainties about public acceptance of the remaining radioactivity, 2) financial costs, and 3) the amount of radioactive waste produced by decommissioning.

Nuclear and/or radiological emergency scenarios

Past accidents in Three Mile Islands, Chernobyl, and the Fukushima Daiichi NPP have changed people's perceptions about nuclear technologies and their risks (Abbott et al., 2006; Latré et al., 2018; Morris-Suzuki, 2014). Uncertainties related to the safety of nuclear installations are one of the main types of uncertainties brought upon when it comes to discussions about nuclear energy. For this reason, in this thesis, apart from decommissioning of nuclear installations, I also focus on nuclear and radiological emergencies as a case study, and the uncertainties present in such situations.

When it comes to nuclear and radiological emergencies, apart from the safety-related uncertainties, other uncertainties involve which protective actions to apply and how to implement them; how to deal with time pressure; how to coordinate cross-border aspects; whether or not people will follow the recommendations they were given; lack-of/contradictory/ambiguous information; ability of emergency response actors to do their job properly; balancing between safety and security; the ability to use new equipment and tools; sufficiency and adequacy of resources; time and direction of the release, and effective organization of distribution of iodine tablets, among others (Perko, Benighaus, et al., 2020a; Tomkiv et al., 2020; Turcanu, Perko, et al., 2020).

In the next section I explain the methods used to address the research questions of this dissertation, as well as how, together with my co-authors, I identified the uncertainties in these two case studies and tested the impacts of their communication.

Research methods applied in the dissertation

Addressing research questions related to a complex, understudied topic such as the impacts of uncertainty communication related to nuclear/radiological risks, requires using multiple methods as well as bringing innovative methods from other research fields. That is why, in this thesis, I apply and/or integrate four different types of methods (scoping review, non-participatory observation, survey embedded experiments, and psychophysiological experiment) in five chapters.

First, in **chapter two**, I conducted a scoping review (N= 33) in order to find out *a) what kind of scientific and societal uncertainties exist in nuclear/radiological risk situations, b) how are uncertainties defined in the literature, c) are there different uncertainties among various actors and research areas, and d) which cases are understudied when it comes to uncertainty communication*. While scoping reviews are characterized with the limitation of not being able to provide implications for practice (Munn et al., 2018), it was the most suitable type of literature review given that the aim of this chapter was to map and bring together the existing literature present in different study areas evolving around a broader research question with scattered evidence (Tricco et al., 2016). Furthermore, I took care of the rigor of the method, credibility, transparency, resonance and ethical criteria by following the guidance from Joanna Briggs Methods Manual for Scoping Reviews (The Joanna Briggs Institute, 2015) and the 'PRISMA extension for scoping reviews' checklist (Tricco et al., 2018) for the collection, analysis and reporting of this review.

Apart from identifying existing uncertainties in literature, in **chapter three**, we were interested *to identify the occurring uncertainties in practice as well, namely in nuclear and/or radiological emergency exercises*. Non-participatory observation (Barner-Barry, 1986) of nuclear/radiological emergency exercises is an ideal method as it offers studying uncertainties in a highly realistic scenario, thus making the results of the study valuable concerning the complexity of the decision-making process under nuclear/radiological risk situations. We observed twelve radiological exercises (three in Belgium, one in Greece, one in Norway, three in the Slovak Republic, one in Slovenia, two in Spain, and one international) at 29 observation points. To make sure that all the necessary ethical aspects of the study were addressed, we applied The *European Code of Conduct for Research Integrity* (ALLEA - All European Academies, 2017) and *Research Ethics in Ethnography/Anthropology* (Iphofen, 2011). While non-obtrusive observation is most of the time a challenge in the beginning of the study, the effects of observers' presence diminish quickly over time (Barner-Barry, 1986; Birdwhistell, 1972), as was the case in our study.

The findings of these two studies suggest that there are different types of uncertainties that various actors are faced with when it comes to nuclear/radiological risks. However, results show that the information about the receivers' side and their reaction to uncertainty communication is understudied. Furthermore, there is no research analyzing the presence of-, communication of-, and decision-making under uncertainties in the case of decommissioning of nuclear installations. For this reason, in the next three studies, I focused on public participation in decision-making procedures related to decommissioning of nuclear installations, as the main point of focus when testing how different actors (i.e. experts vs. public) react to uncertainty communication. Research shows that experts perceive lower radiological risks than laypeople because of their familiarity with the issue (Perko, 2014). Hence, in this thesis I decided to compare experts versus laypeople's reactions towards uncertainty communication. The expectation is that experts are least likely to have a strong emotional reaction towards uncertainty communication given they face uncertainties on a regular basis, and they are more willing to participate in decision-making procedures about decommissioning of nuclear installations, given their familiarity with the topic. On the other hand, I expect that laypeople are a most-likely case for finding a reaction towards uncertainty communication, given that uncertainty is very often excluded from communication to the public (Harris, 2015; Jensen et al., 2011), but the more uninformed they feel about decommissioning, the less they are likely to be willing to participate.

As part of this goal, in **chapter four**, I was first interested to study who is willing to participate in decision-making procedures related to decommissioning of nuclear installation in Belgium, namely what influences public's intent to participate. To do so, I used data from a face-to-face public opinion survey conducted in 2015 with a representative sample for the Belgian population aged over 18 (N= 1028). While one disadvantage of public opinion surveys is nonresponse bias, using a face-to-face interviewing approach already reduces this bias to a great extent (Hox & De Leeuw, 1994). Another potential limitation as part of this survey is the use of a hypothetical question related to public participation intention. In this survey we asked respondents "to what extent would you like to participate in decision-making about nuclear power plants?" However, studies on public participation have found there to be a difference between intended versus actual participation (Ajzen, 1985; Ajzen et al., 2004; Quintelier & Blais, 2016). For instance, in political science studies, it has been found that there are issues with voting over-reporting in surveys (Belli et al., 1999). For this reason, a comparison of intended versus actual behavior when it comes to public participation in decision-making about decommissioning of nuclear installations is needed. We address this issue in chapter 5 (explained in the next paragraph). Acquiescence bias was also taken care of by paying special attention to the framing of the questions and answering categories as well as by adding additional items on personality traits of the respondents (Turcanu et al., 2015). Results showed that interest on the topic, and radiological risk perception, had direct effects on public participation intention concerning decommissioning of nuclear installations. Other variables such as trust, attitude towards nuclear energy, political ideology, and living in the vicinity of a nuclear installation also influenced the intent to participate. After setting the stage with identifying factors influencing participation intention about decommissioning in Belgium, I then moved on to add uncertainty communication as an additional explanatory variable.

Chapter five uses data from a survey-embedded experiment conducted in 2021 with a representative sample of the Belgian population aged over 18 (n= 1060). This survey was online (Computer Assisted Web Interviewing – CAWI) due to the COVID-19 pandemic (Hoti, Perko, & Turcanu, 2021). While online surveys run a higher risk of nonresponse bias than face to face surveys (Hox & De Leeuw, 1994), to address this issue, in this survey we used incentives, which are proven to increase motivation to participate in surveys and thus reduce the chance for nonresponse bias (Pforr et al., 2015). Additionally, special attention has been paid to the formulation of questions (neutral statements, no leading questions, insertion manipulation checks) in order to avoid social desirability and acquiescence bias. As part of the third objective of this thesis, in this chapter I was not only interested to test the impact of uncertainty communication on public participation intention, but also to test the mediating effect of feelings, given the contradictory findings in the literature. Hence, I conducted a 4x2 (4 groups testing uncertainty communication (3 experimental, 1 control group) x 2 groups measuring intended versus actual participation) experiment. After discussing with several experts in the field of decommissioning, we identified 3 main types of uncertainties that experts are faced with when it comes to decommissioning of nuclear installations, and that might be relevant for the Belgian population. This way, apart from introduction to decommissioning, the first experimental group received also an uncertainty about *1) public's acceptance of remaining radioactivity on the site*; the second experimental group received an uncertainty about *2) the amount of radioactive waste resulting from the decommissioning*; and the last experimental group received an uncertainty about the *3) financial constraints related to the decommissioning process.* An ethical approval for this experiment was obtained from the ethical committee of the University of Antwerp in Belgium (dossier number: SHW_20_77). Using a survey embedded experiment thus allows for obtaining large-scale results, that are representative for the Belgian population over the age of 18 and for the first time test the impact of uncertainty communication related to the topic of decommissioning of nuclear installations.

Finally, in **chapter six**, in 2021, I conducted a psychophysiological experiment with employees of nuclear/radiological-related institutions in Belgium, divided in 2 groups: familiar and unfamiliar with decommissioning. More specifically, the sample consisted of N=134 employees of the Belgian Nuclear Research Centre (SCK CEN); VITO (an independent Flemish research organization in the area of clean technology and sustainable development); and Belgoprocess (company responsible for the safe processing of radioactive waste produced in Belgium).

This chapter uses a similar experiment, as the one explained above, but it goes more in depth concerning the mediating effects of feelings and emotional arousal. In this study, in addition to feelings, emotional arousal is measured with a Galvanic-Skin-Response (GSR) device which respondents had to keep on their hands while filling-in the survey in our lab's computer. This device measured the electro dermal activity (EDA) of the participants throughout the survey, which records the electrical signal by electrodes applied to the skin. EDA has been proven to be the most useful index of emotional arousal as it is the only autonomic psychophysiological variable that is not contaminated by parasympathetic activity (Braithwaite et al., 2013; Caruelle et al., 2019). However, a potential bias to this measurement can be the random noise and distractions among participants. For this reason, I paid specific attention to removing all potential disturbances from the lab during the time of the experiment. Additionally, for this study, it was only relevant to analyze the change in arousal from the moment the participant was encountered with uncertainty information, so the level of arousal of participants before the experiment was not a risk for bias in the results.

Given that the aim of this study was also to test the impact of uncertainty communication on feelings, emotional arousal and participation intention about decommissioning, I used the same three uncertainties. These uncertainties were given in separate slides in order to see the impact that each type of uncertainty has on participants' EDA. Each uncertainty was present on the screen for 25 seconds, which based on the pre-testing of the survey, deemed to be an adequate time for processing of the type of the uncertainty. For this experiment, the ethical approval was issued by the ethical committee of University of Antwerp with reference number SHW_20_105.

The findings of all these studies were presented in international scientific conferences and discussed with experts on risk and uncertainty communication as well as nuclear, and methodological experts, before undergoing the peer-reviewed process of scientific publication. The figure below illustrates the outline and the structure of the dissertation.

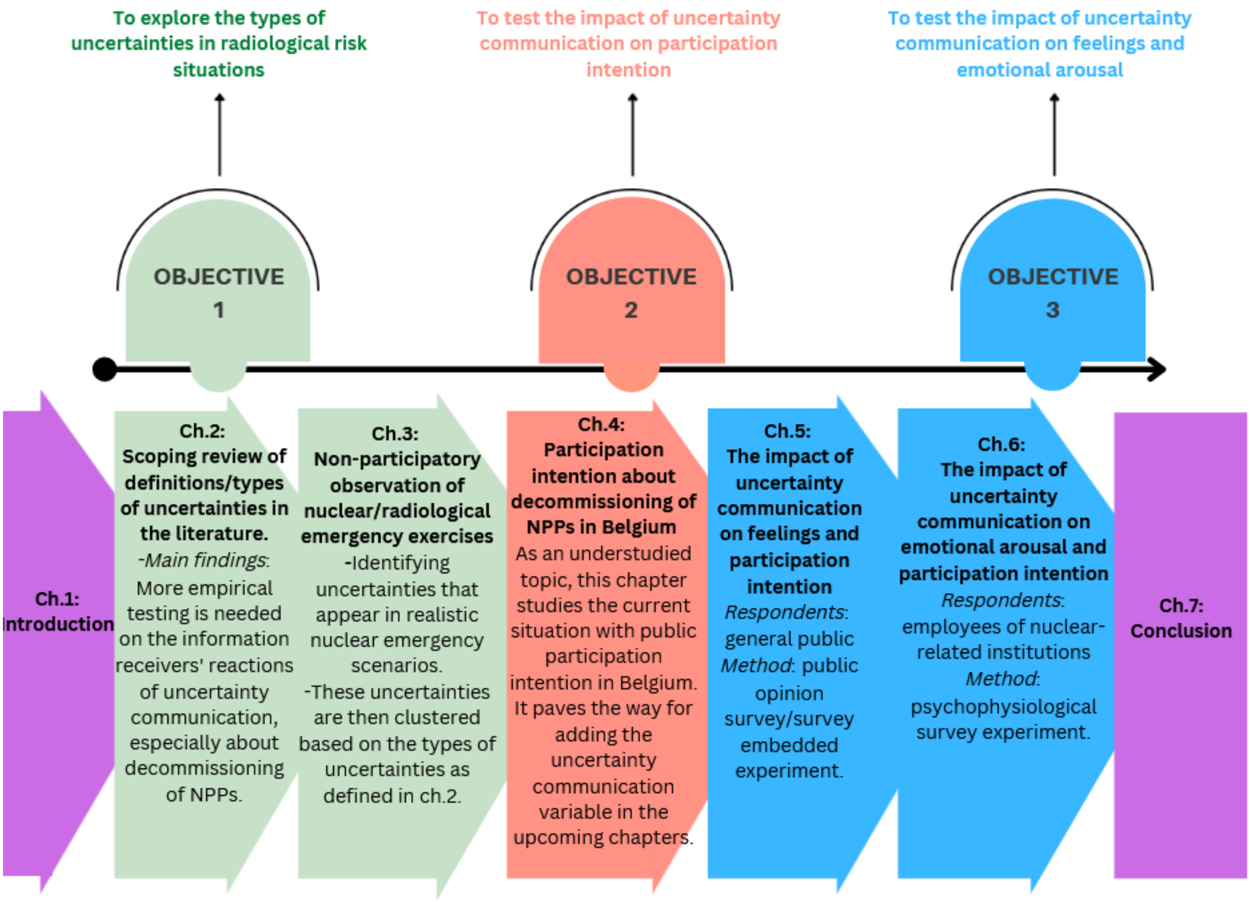

Figure 2. Outline and structure of the dissertation.

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Chapter 2: Radiation risks and uncertainties: a scoping review to support communication and informed decision-making

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Abstract

Although radiation protection is challenged by many uncertainties, there is no systematic study investigating the definitions and types of these uncertainties. To address this gap, in this paper we offer a scoping review to comprehensively analyze, for the first time, peer-reviewed scientific articles (n=33) related to uncertainties in the following radiation exposure situations: nuclear emergencies, decommissioning of nuclear/radiological installations, and long-term radiological exposure situations (e.g. NORM). Results suggest that *firstly,* there is no agreement regarding definitions of uncertainty, which is mainly defined based on its sources, types or categories rather than by its meaning. S*econdly*, different actors are faced with different types of uncertainties. Uncertainties of scientific community are mostly data and methodology-driven (e.g. dose-response relationships), those of the decision-makers are related to the likely consequences of decision options and public reactions, while laypeople's uncertainties are mainly related to trustworthiness of experts or the emotional potential of specific risk exposures. Furthermore, the majority of articles focus on the uncertainties of the scientific community, while those of the information receivers (i.e. decision-makers and laypeople) receive much less consideration. *Finally,* there was no difference in types of uncertainties across the different risk-related

study areas analyzed (radiation vs. other risks). Based on these findings, we provide some preliminary recommendations regarding both, research on uncertainty related to radiation protection, as well as, communication practices.

Keywords: Uncertainty; radiation risks; communication; decision-making

Uncertainties in radiation protection

The field of radiation[1] protection is challenged by associated scientific, technical and societal uncertainties related to ionizing radiation. In the last decade, more attention has been paid to different aspects such as uncertainty evaluation and expression in dose and risk assessment (Allisy-Roberts & Day, 2008). However, there still remains a gap on uncertainties related to different applications as well as understanding and evaluating risks of ionizing radiation in specific, and radiation protection in general. For instance, uncertainties linked with exposure assessment may be related to the physicochemical behaviour and transport of radionuclides, transfer to biota, dosimetry and dose assessment in humans and biota (Hinton et al., 2013). Another uncertainty concerns the possible relationship between background irradiation and cancer occurrence, particularly in children as they are substantially more sensitive to radiation exposure than adults (Hoeschen, 2018; UNSCEAR, 2013, 2017; Wakeford et al., 2009). Moreover, assessment of occupational exposure from incorporated radionuclides is still subject to major uncertainties, due to activity measurement errors, individual variability, limited biokinetic and dosimetric models and unknown parameters of exposure (Boice, 2010; Kreuzer et al., 2018). It is recognised that also nuclear or radiological emergency response and recovery requires decisions under high uncertainty (Schneider et al., 2017). Existing research argues that these uncertainties need to be communicated (Allisy-Roberts & Day, 2008; Fischhoff

[1] Following the comments of the anonymous reviewers, the word 'radiological' has been replaced with 'radiation' as the former represents a more ambiguous term given that it is used also for a medical specialty and diagnostic imaging. The latter, on the other hand is more general and less ambiguous.

& Davis, 2014; Osman et al., 2019; Renn, 2008b) in order to empower laypeople (patients, workers, exposed population…) as well as decision-makers to take informed decisions considering risks and benefits of exposures to ionising radiation. This requires a good understanding of laypeople's and decision-makers' sense-making of ionising radiation concepts and related uncertainties (Christofides et al., 2010).

According to the recent 'Strategic research agenda for social sciences and humanities in radiological protection' (Perko et al., 2019), it is important that we capture different understandings of uncertainties related to radiation risks in order to bridge the gap between different concepts of uncertainty across various actors and research fields. To address the complexity of assessing causal and temporal relationships as well as sources of uncertainty related to radiation protection, existing research suggests that an analysis of the state-of-the-art knowledge is needed (Perko, Van Oudheusden, et al., 2019). This would help in identifying and prioritizing critical uncertainties, which is essential to decision-making (van Asselt & Rotmans, 2002; Walker et al., 2003) related to radiation protection.

After acknowledging the relevance of uncertainty communication, numerous studies have been conducted regarding uncertainty and its related aspects such as uncertainty analysis, classification, communication and decision-making under uncertain situations (N. B. Beck et al., 2016; Knoblauch et al., 2018; Maxim & Van der Sluijs, 2007; Walker et al., 2003). These studies are present in different publications, are from different study fields, take into account the uncertainties of different actors and deal with different aspects of uncertainty. However, in the radiation protection field, there is no systematic study investigating the definitions and types of uncertainties. To address this gap, we conducted a scoping review to systematically analyze, for the first time, the uncertainties related to the following radiation exposure situations: nuclear emergencies, decommissioning of nuclear/radiological installations, and long-term radiological exposure situations (e.g. NORM). For the purpose of this study, we preferred to focus on these three cases, since they represent core concerns of the European Commission (H2020 projects) and are less covered by scientific scrutiny than for example routine emissions from power plants. For instance, related to nuclear emergencies, many gaps and issues have been identified (especially after the Chernobyl and Fukushima accidents) that need to be addressed. Such issues involve creating and advancing different modelling and monitoring techniques; dealing with contaminated goods; improving decision support systems; issuing reliable and trustworthy information to the public in due time; as well as analyzing public's perceptions of risks and uncertainties (Raskob, 2017; Schneider et al., 2017). Similarly, the TERRITORIES project under H2020 (Guillevic et al., 2018), has clearly argued that more scientific attention needs to be paid on the impact of uncertainty on decision-making regarding long term radiological exposure situations (e.g. NORM). Likewise, decommissioning of nuclear/radiological installations is also associated with many challenges and uncertainties which, if unaddressed, may result in unacceptable health, safety and security risks to the general public and to workers and increased risks to the environment (International Atomic Energy Agency (IAEA), 2016).

By analyzing the uncertainties present in the literature that treats different actors as respondents, we will be able to see the different uncertainties that these actors are faced with, thereby making it easier to realize what kind of information needs to be communicated to reduce uncertainties and allow information receivers make informed decisions in radiation exposure situations.

In the next sections, we provide more precise clarifications to the concepts used in this scoping review as well as a theoretical background for the methods and analysis conducted. Afterwards, we present, interpret and discuss the results and finally we conclude the paper by pointing out the main results, limitations of the study as well as recommendations for the radiation protection community.

Theoretical and conceptual background

There is an extensive literature on risk perception, communication and governance in general (Fischhoff, 2012; Renn, 2008b; Slovic, 1993; Slovic et al., 2004), mainly arguing that investigating risk and uncertainty perception provides relevant background information for designing effective communication, structuring public discourse, informing judgments about risk acceptability and affecting public policy making (Renn, 2012). However, the literature related to communication of- and decision making under uncertainties in the radiation protection field remains scarce and scattered.

The theoretical and conceptual background of this scoping review is based on context of uncertainty communication and/or decision-making under uncertain situations. Following Harris (2015), we define *uncertainty communication* as a process of communicating uncertain information a) between actors in the scientific community, b) from scientific community towards other actors such as decision-makers, media and laypeople or c) bottom-up uncertainty communication, namely from laypeople towards decision-makers or scientists. On the other hand, we define *decision-making under uncertainty* as a process of choosing among several options for taking action (including doing nothing), in situations where there is contradictory, ambiguous, imprecise or no information at all (Renn, 2008a). One of the main rationales of effectively communicating uncertainty is to help the receivers of the information make informed judgments and decisions to achieve the long as well as short-term goals (Patt & Weber, 2014). On the contrary, failure in communication results in a lack of public trust in scientists, who seem not to know the needs of laypeople, and scientists' trust in the public, who seem unable to understand uncertain information (Fischhoff, 2012). The same was argued to apply to authorities using science to base their decision-making and communication (Perko, 2016). For this reason, it deemed relevant to focus on these two aspects of uncertainty and the linkage between them while reviewing the literature to answer our main research question, namely *what are the existing definitions and types of uncertainties in radiation risk literature (RQ1)?*

The classifications of uncertainty published in the literature are numerous and diverse (Maxim & van der Sluijs, 2011). Yet, different authors argue that in the process of uncertainty communication, an important aspect is neglected, namely, the differences in types of uncertainty across different actors (Maxim et al., 2013; Morris-Suzuki, 2014). Although aiming to contribute to informed decision-making (Doyle, McClure, Paton, et al., 2014b), communicating scientific uncertainties does not necessarily satisfy or decrease, the uncertainties of laypeople. As Maxim et al. (2013) argue, laypeople, raise different and more uncertainties than those of the scientists. Furthermore, not all uncertainties- especially uncertainty due to low dose radiation risks, behavioral and societal variability, value diversity, technological surprise, ignorance and indeterminacy- can be adequately addressed with existing methods and tools (van Asselt & Rotmans, 2002). Similarly, Walker et al. (2010) argue that it is important to distinguish between what can be called the scientists' view of uncertainty and the decision-makers'/policymakers' view of uncertainty. The existing typologies of uncertainty mainly focus on the perspective of the ''producer'' of uncertainty information, thereby assuming that the message about uncertainty does not change when it is communicated between the producer (e.g. the scientist/modeler) and the information receiver (e.g. the decision-maker or laypeople) (Maxim & van der Sluijs, 2011). For this reason, uncertainty is usually treated as a "marginal issue, as an additional physical variable, as a mathematical artifact" (Asselt & Rotmans, 2002: 82). In any communication process, the messages produced and received are not identical. Ignoring this impacts the ultimate success of uncertainty communication (Maxim & van der Sluijs, 2011) and poses serious problems for the scientists when delivering forecasts to the public through the press (Harris, 2015). Furthermore, van Asselt (2005) takes into account the fact that uncertainty is a social construction, thereby naming the 'constructors' as 'artists' which shape and reshape the concept of uncertainty. "If we want to understand the uncertainty challenge" she argues, "we have to take the artists into account as well" (van Asselt, 2005). Based on these arguments, in this research, we will analyze *whether there are different types of uncertainties across different actors present in the literature review (RQ 1.1)* as a first sub-question of this research.

Following Harris (2015) we divide the main actors present in literature regarding uncertainty from a communication-and-decision-making-centered point of view in three groups: *1) scientific community*- involving academia, scientific experts, observatories and other actors dealing with information and advice; *2) decision-makers*- involving governmental bodies, policy-makers, regulators, enforcers, emergency actors, etc.; and *3) laypeople and other actors*- involving citizens, media, non-governmental organizations, and the like (Harris, 2015). It is important to state that this is not simply an issue of 'scientists versus non-scientists'. It is more of an epistemological issue (Morris-Suzuki, 2014) so, depending on the situation and issue at hand, even a member of the scientific community can be considered as a layperson in a particular case. In the case of the Fukushima disaster, there were uncertainties and criticisms towards the application of science in disaster response even between the scientists themselves (Morris-Suzuki, 2014). This will be carefully taken into account when analyzing the position and stakes of the actors while identifying the types and definitions of uncertainty.

In spite of the differences in uncertainties across different actors, scholars argue that epistemological differences amongst different study areas have contributed even more to the difficulty of finding a consensus regarding uncertainty. Additionally, different articles use different names for the same thing, or the opposite (the same name for different things) when talking about uncertainty (Romao & Pauperio, 2016). The various existing uncertainty definitions and typologies hinder clear communication and consequently the understanding of existing uncertainties in the field of natural hazards according to Kunz, et al. (2011). These arguments lead to the formulation of the second sub-question of this paper, respectively*, do uncertainty definitions and types in the radiation risk research literature differ from the definitions and types in other risk-related study areas (RQ 1.2)?* This way, we can see whether we can make generalizations when we talk about uncertainty across different fields.

The goal of this scoping review is, hence, three-fold: First, it will inductively review and summarize the existing definitions of uncertainties by focusing on the different terms, concepts, and types used to define it. Second, the focus will shift towards the types of uncertainties that are present amongst various actors (i.e. scientific community; decision-makers; and laypeople) in literature. Third, we will analyze whether there are differences in definitions and types of uncertainty between radiation risk research and other study areas. Conclusively, the findings of this scoping review will be placed into the deeper context of what they mean for communication of uncertainties and decision-making in the radiation field.

Search method and analysis

In this paper we employed a scoping review as a method following the guidance from Joanna Briggs Methods Manual for Scoping Reviews (The Joanna Briggs Institute, 2015). This type of literature review proved to be most suitable given that the aim of this paper is to map and bring together the existing literature present in different study areas evolving around a broader research question with scattered evidence (Tricco et al., 2016). A review protocol with basic planning and expectations was created internally, but not registered or made public. As a part of comprehensively reviewing the body of the literature, we use 'PRISMA extension for scoping reviews' checklist (Tricco et al., 2018) for the collection, analysis and reporting of this review.

Articles for the scoping review were collected in December 2018 in two search engines: Web of Science and Scopus. Web of Science covers a range of published articles from the year 1972, while Scopus covers articles starting from 1960. The combination of keywords was decided based on the three research questions of a larger research, part of which is this literature review focusing specifically on the first research question, namely on types and definitions of uncertainties in the context of communication and/or decision-making. The keyword search was automatic and included the following: *'Uncertain*' AND 'Communicat*' AND 'Decision*' AND 'Risk' in combination with 'Emergency' OR 'Radioactiv*' OR 'Accident*' OR 'Disaster' OR 'Expos*' OR 'Decommission*' OR 'Nuclear'* (see table 1).

The criteria applied during evaluation of titles and abstracts were: *the document had to be (1) a research article; (2) published in a peer-reviewed journal; (3) be related to uncertainties; (4) be related to decision-making and/or communication; (5) at least three of the keywords (two from main keywords and 1 from the combination section) have to be present in the abstract; and (6) has to be in the English language.*

The search resulted in 423 hits (see figure 1). After removing the duplicates, 224 articles remained whose abstracts were evaluated in order to be able to select the relevant ones for further analysis. The years in which the resulting hits are published range from 1992-2018. After screening the titles and abstracts, 60 articles were downloaded for deeper reading and analysis. During the detailed reading, 27 more articles were considered irrelevant either because they did not meet the selection criteria based on the full text or they were not useful to answer our research questions (e.g. did not include/mention any definitions or types of uncertainty). Finally, we chose 33 articles for final analysis (see annex 4 for a list of articles). The years in which these articles were published range from 2002-2018.

The analysis approach for the articles was two-fold. Using grounded theory as a method for rigorous analysis of the review (Wolfswinkel et al., 2013), we first applied an inductive (bottom-up) approach, where we created and modified codes in NVivo[2] based on the content of the articles and then a deductive approach to analyze the relationship among the coding categories. This means that the first approach was open coding which was then followed by axial and selective coding (Wolfswinkel et al., 2013). The coding process was done by the main researcher, but it has been supervised and confirmed by the other authors. In order to make sure the method of the paper meets the rich rigor, sincerity, credibility, transparency, resonance and ethical criteria, the recommendations for good

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[2] NVivo is a software package for Qualitative Data Analysis (QDA). It supports QDA by managing and organizing data, managing ideas, querying data, graphically modeling ideas and concepts as well as reporting from the data (Bergin, 2011).

qualitative research (Tracy, 2010) as well as PRISMA guidelines for scoping reviews (Tricco et al., 2018) have been consulted. The data charting related to definitions and types of uncertainty were created inductively, without any pre-determination or expectation. Other data relevant for charting for this analysis included the publication year, study area, methodology, main variables, respondents and N (if applicable), the actor to whom a type of uncertainty belongs (this was decided based on the respondents participating in the study or when the author mentions a type of uncertainty belonging to a type of actor), as well as who is talking about a particular type of uncertainty (i.e. is it the laypeople talking about their uncertainties or the scientists saying what laypeople's uncertainties are?). The articles that served as material for the scoping review are listed in annex 4.

Table 1. The keywords used in literature search.

Main keywords ("AND")[3]	**Together with ("OR")**	**resulting number of hits**	
		Web of Science	Scopus
Uncertaint*	Emergency	N= 44	N= 45
Communicat*	Radioactiv*	N= 4	N= 8
Decision*	Accident	N= 9	N= 35
Risk	Disaster	N= 28	N= 39
	Expos*	N= 82	N= 87
	Decommission*	N= 1	N= 1
	Nuclear	N= 17	N= 25

[3] The conjunction "and" is used between the main keywords whereas the conjunction "or" is used between the other keywords which are in combination with the main ones.

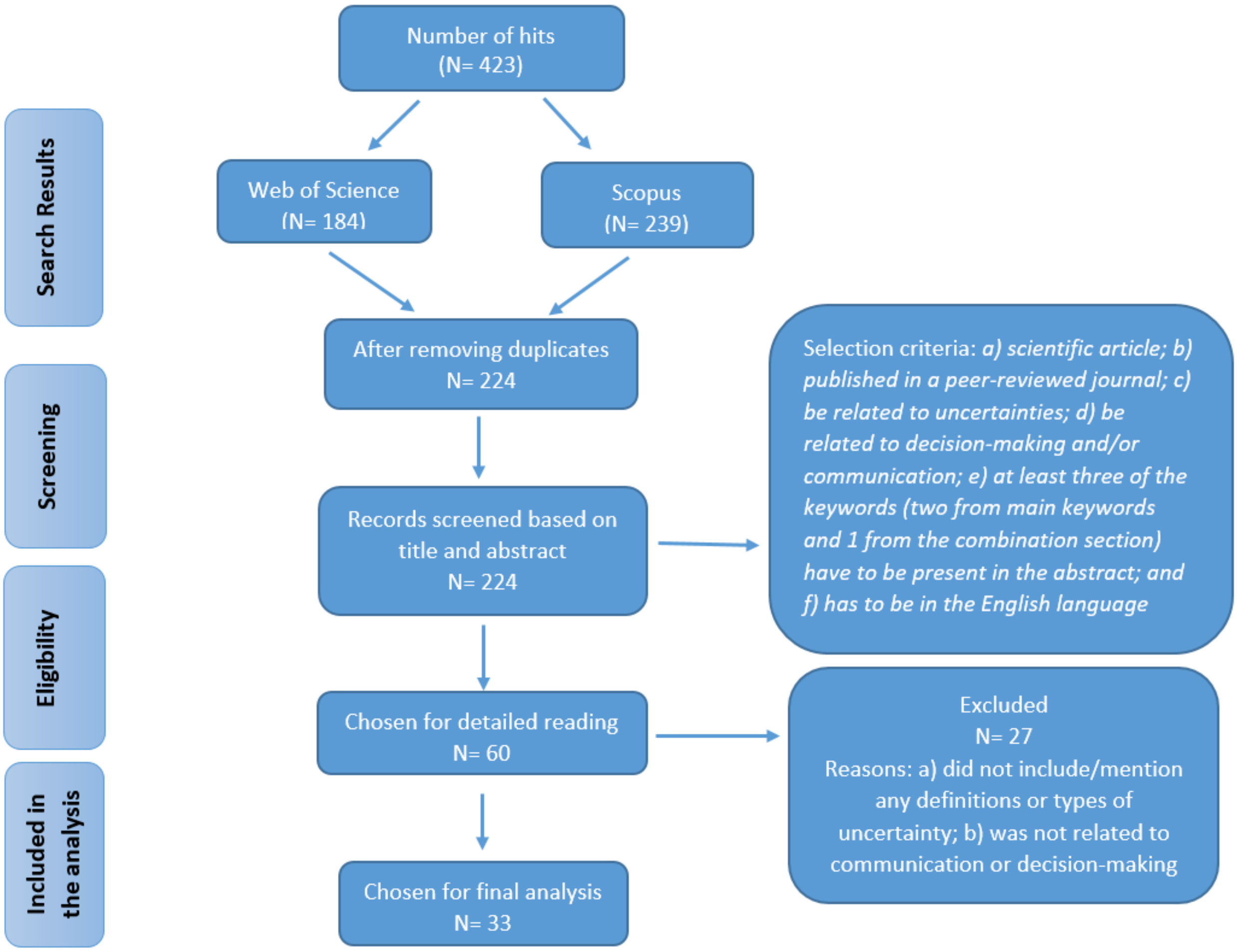

Fig. 1. Literature search and selection flow

Results

Definition of uncertainty

The results of this scoping review point out that out of 33 articles, only 19 of them include definitions of uncertainty. The other articles included in the analysis only mention types or use examples of uncertainty without explicitly defining what it means. Even these 19 articles define uncertainty in multiple and different ways.

As table 2 (see appendix 1) indicates, 6 out of 19 articles try to define uncertainty based on its *meaning* (i.e. what is meant by the concept of uncertainty). For example, Walker et al. (2003: 8) defines it as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”, while Han (2012: 165) argues that “uncertainty is a ‘metacognition’—a thinking about thinking—characterized by self-awareness of incomplete knowledge about some aspect of the world”. Similarly, also related to perceptions, Maxim et al. (2013: 679) argues that “uncertainty (…) refers to the situation that the body of evidence from scientific research is (perceived to be) inconclusive”. Morris-Suzuki (2014: 349) makes a distinction between uncertainty and ignorance by saying that “uncertainty is the situation where the broad parameters of a risk are understood but science is not (or not yet) capable of accurately assessing the odds”. “In a situation of uncertainty,” she continues, “we are aware that there are variables we cannot predict; but in a situation of ignorance, we do not know what it is that we don’t know”. Harris (2015: 30) on the other hand, says that “uncertainty implies ignorance”. Another definition is made by Fearnley (2013: 1899) who explains uncertainty as a “state of incomplete knowledge” involving complex, non-linear and open systems.

Speaking of incomplete knowledge, the majority of the authors (Han, 2012; Kox et al., 2015; Levin et al., 2004; Romao & Pauperio, 2016) see it as a *source* (i.e. cause or originating place of uncertainty) rather than a state or condition. Such sources of uncertainty mainly include uncertainties arising due to lack of knowledge (Levin et al., 2004; Thompson, 2002); due to randomness or variability (Kox et al., 2015; Romao & Pauperio, 2016); from the complexity of understanding different phenomena, from the difficulties encountered in decision-making processes (Laes et al., 2005); arising from vague, ambiguous expressions (Han, 2012; Romao & Pauperio, 2016); etcetera. Based on these originating sources, authors then attempted to group different types (i.e. categories) of uncertainties and create typologies when explaining what uncertainty means.

The most commonly used typology is the *epistemic and aleatory uncertainty* distinction (Doyle, McClure, Paton, et al., 2014; Knoblauch et al., 2018; Markon, Crowe, & Lemyre, 2013). Apart from these two types, the typologies present in the literature cover different types of uncertainties as well.

Epistemic uncertainty is mainly related to the unknowns (Doyle, McClure, Paton, et al., 2014b). It is defined as a state of mind and a reflection of our own incomplete knowledge

(Eiser et al., 2012b; Harris, 2015; Thompson, 2002). Given that it is knowledge-based, it can be reduced with the gain of new knowledge (Knoblauch et al., 2018). However, this is not always the case since obtaining more knowledge can point out some things we did not know or think of before, therefore increasing or adding more uncertainty (Romao & Pauperio, 2016; van Asselt, 2005; Walker et al., 2003). Imagine you draw only red and blue balls from an urn. After 50 trials you believe that there are only blue and red balls in the urn. In the 51st trial you draw a green ball and immediately your inference about the system becomes fuzzier. Now you have to deal with three possible outcomes and your probability assessment about the composition of the urn needs to be re-done and will expand your confidence interval for your assessment (Fox & Ulkumen, 2011).

According to Levin *et al.* (2004: 36) epistemic uncertainty refers to the degree of belief and credibility and is mainly expressed with the statements 'has been considered by some', 'it is generally believed', and 'it appears that'. Hence, the indicators of epistemic uncertainty are words and expressions that indicate less than full confidence in, or commitment to, the content of a statement (Levin et al., 2004).

Aleatory uncertainty is also referred to as stochastic uncertainty which is random (Doyle, McClure, Paton, et al., 2014; Maxim, 2014; Romao & Pauperio, 2016) and dependent on the nature of the things for which we seek knowledge (Eiser et al., 2012b). Knoblauch, Stauffacher, and Trutnevyte (2018) argue that this type of uncertainty is irreducible. Maxim (2013: 685) explains it as "the randomness of natural differences between individuals in, e.g. their reaction to chemicals" or "the time between the consecutive occurrence of disasters such as earthquakes of a given intensity" as Romao and Pauperio (2016: 4) state. Aleatory uncertainty can be either be based on statistical distributions (such a throwing a dice) or variability without any recognizable statistical pattern (occurrence of earthquakes). The latter may be true because of the rareness of the event that does not allow a statistical representation or it seems to be totally randomized without any regularity in occurrence or severity. Aleatory uncertainty is also known as natural *variability* which is especially applicable in human and natural systems and concerning social, economic, and technological developments (Walker et al., 2003). Bier and Lin (2013) mentioned that variability reflects differences among the members of a heterogeneous population. A similar definition was made by Thompson (2002) who says that variability refers to real and identifiable differences between individuals within a population addressed by the risk assessment. However, this author argues that uncertainty and variability are two different things and they have to be distinguished (Thompson, 2002). Variability refers to real differences between individuals of a population. Therefore, decision-making under uncertainty requires judging how probable it is that risks will be over- or underestimated for every member of a population, while variability requires taking into account the certainty that "different individuals will be subjected to risks both above and below any reference point one chooses." (Thompson, 2002: 648).

The distinction between epistemic and aleatory uncertainty is, however, not always evident. Bier and Lin (2013) mention two other terms that are used in literature as types of uncertainty. These include 'outcome uncertainty' and 'assessment uncertainty'. Outcome uncertainty is related to what might happen and with what probability and according to Bier and Lin (2013), this source of uncertainty reflects both state-of-knowledge uncertainty and population variability, while putting together epistemic and aleatory uncertainty. Assessment uncertainty, on the other hand, is related to the state-of-knowledge uncertainty, namely, how much the results of the analysis might change with additional information (Bier & Lin, 2013) which in this case, is just another term used for epistemic uncertainty. Likewise, Laes *et al.* (2005) mention the term 'cognitive uncertainty' when referring to 'epistemic uncertainty'. They argue that cognitive uncertainty may be generated as the understanding of phenomena becomes even more difficult, and at the same time, principal limits of knowledge emerge. This is often called the 'problem of expertise' or lack of uncontested factual knowledge with which decision-makers are faced (Laes *et al*. 2005).

Ambiguity has been mentioned as another type of uncertainty by many authors. This is when a word can be used in more than one way and it is not clear in which way it is being used from the given context (Markon et al., 2013). It denotes the possibility of interpreting knowledge in different ways or draw different normative conclusions from an identical set of evidence. The same source is termed as ‘contentual uncertainty’ by (Levin *et al.* 2004) while Kox *et al.* (2015) divide it into ‘context-dependence' which points to the fact that a statement can have different meanings in different contexts; ‘underspecificity’ which shows that the term is not as specific as needed; and ‘vagueness’ which arises from unspecific use of a term in a borderline-case sense (Kox *et al.* 2015). Romao and Pauperio (2016) define this source as ‘linguistic’ uncertainty which differs from aleatory and epistemic uncertainties since it does not belong to the data under analysis, and it is not created by processing available data. Instead, linguistic uncertainty is created when trying to express information using non-quantitative metrics (Romao & Pauperio, 2016). There are arguments that ambiguity is different than uncertainty, the former implying lack of meaningful interpretation and the latter defined as shortage in information. But, van Asselt (2005) argues that ambiguity (interpretational plurality) is a phenomenon of uncertainty rather than a distinguished part.

Another type mentioned in the literature is *decision* uncertainty. It occurs in the process of decision- making based on the interpretation of results that were expressed and communicated. In this process, different individuals can have different interpretations of the same data due to subjective judgment or differences in values, beliefs, and preferences and therefore make decisions in different manners (Romao & Pauperio, 2016). Similarly, Laes *et al.* (2005: 358) use the term ‘pragmatic uncertainty’ to explain “the uncertainties resulting from the difficulties encountered in policy-making processes to reach conclusions and to implement decisions in a turbulent social environment. As is the case with the other types of uncertainties, decision uncertainty has also been termed in different ways and sometimes even blended with ambiguity such as in the case of low-dose (ionizing and non-ionizing) radiation (Renn, 2008b).

Maxim (2014) also argues that there are more types of uncertainties in addition to the ‘epistemic-aleatory-ambiguity’ distinction. These include *technical uncertainties* which are mainly technical errors caused by imprecise instruments or measurement methods; *methodological uncertainties* which include methodological challenges such as making assumptions when knowledge is missing or choosing among several available methods for assessing a parameter; *normative uncertainties* which include interpretation of raw data and conclusions about the level of evidence they provide; as well as *communication uncertainties* which include how completely and understandably the research is reported (Maxim, 2014: 5).

It is also important to distinguish *expressed* uncertainty from *perceived* uncertainty because the scientific message transforms as it is communicated from the emitter (i.e. the scientist) to the receiver (i.e. laypeople) (Maxim et al., 2013). Expressed uncertainty includes situations when a scientist says they do not know; a scientist says they are not sure/confident in their results; or different scientists disagree, even if each is fully confident in their assertions (e.g. the GMO debate) (Maxim et al., 2013).On the other hand, perceived uncertainty includes situations in which laypeople ask questions about the scientific information received; have doubts about or lack trust in the scientific information received; criticize the assumptions and choices made by scientists when producing or interpreting information; point out contradictions among experts; and point out the fact that they do not understand the scientific information received (Maxim et al., 2013).

Uncertainties across different actors

In this section we present the results of the research question related to different types of uncertainties across different actors such as the scientific community, decision-makers and the laypeople.

Uncertainties amongst the scientific community

In the studies that employ scientists as respondents (n=15), or mention the uncertainties of the scientific community, as explained in table 3 (appendix 2), the majority of the uncertainties mentioned are of *methodological* nature. For instance, in a study related to emerging contaminants, based on in-depth interviews with scientists, Cordner & Brown (2013: 469) came to the conclusion that scientific uncertainties are caused by four sources of ethical concerns: "1) choosing research questions or methods, 2) interpreting scientific results, 3) communicating results to multiple publics, and 4) applying results for policymaking". Similarly, based on a survey with 34 natural hazards experts, Kunz et al. (2011: 1737) argue that uncertainty is related to the components of data quality such as error or accuracy, precision, completeness, consistency, and currency as well as other elements such as credibility, subjectivity, and interrelatedness. Levin et al. (2004: 33) echoes this based on a content analysis where he relates scientific uncertainty with the study methods, namely to the quality and relevance of the study design, extrapolations, data gaps, the way the study is performed, and how the results are reported. According to Oberg & Bergback (2005) acquiring more and better data can reduce uncertainty. This applies to uncertainty in "model structure, parameter estimates and exposure scenarios" (Oberg & Bergback, 2005: 215). Model and parameter uncertainty are also mentioned by Linkov et al. (2006) in their study using model inter-comparisons to address model uncertainties.

Another type of uncertainty mentioned by the scientific community present in the literature is related to the *communication* process. Some aspects of this type of uncertainty, as Han (2012) states based on a literature review, are conceptual and relate to questions about the meaning and nature of what we are communicating. Other aspects are more practical, namely how to communicate these uncertainties? An additional example comes from the study of Drew et al. (2003: 266) based on focus groups with scientists arguing that there is a need for more knowledge and education on how to raise the public understanding of risk by explaining the differences between uncertainty and variability in data.

Furthermore, there are *ethical* aspects related to communicating information that is relevant but which is subject to potential harm or consequences (Han, 2012: 155). A similar conclusion has been drawn by Fearnley (2013) following her in-depth interviews with 93 scientists. A quote from a scientist in her study states that they are torn between the desire to remain neutral by issuing only the scientific information versus providing additional information on the hazard and risk which is considered essential. The practice of uncertainty communication is also associated with conflicts on whether to give recommendations on decision-making or not. One scientist in this study stated: "I don't think that we scientists should strive to make the jobs of public officials any easier. I think that we should tell them honestly what we don't know as well as what we know, they have tough choices to make and should not be spoon-fed" (Fearnley, 2013: 1906). Another issue mentioned in a literature review from Harris (2015) related to communication of uncertainties is the impact that media can have on this communication process. Scientists reported that their statements get misquoted in the media stories and that reporters are not prepared or aware of the subject they are writing about (Harris, 2015: 20).

Furthermore, there are *epistemic* and *aleatory* uncertainties mentioned amongst the scientists in the literature such as uncertainty to low dose risks (e.g. linear no-threshold theory) (Mossman, 2009: 104); variability among the risks posed by different nuclear power plants; epistemic uncertainty about the average risk in a population of similar power plants (Bier & Lin, 2013: 1900); uncertainty over the probability of an event as well as uncertainty over the value of the consequences, mainly because 'value' can have different meanings (Eiser et al., 2012: 7).

Decision-related uncertainties are also mentioned in the literature related to the scientific community. For example, in a study using interviews with forecasters about flash flood risks, Morss, Demuth, Bostrom, Lazo, & Lazrus (2015) found that forecasters are uncertain in monitoring and predicting these events. This poses a problem in deciding when to release warnings. For example, if a warning is released too early, you risk raising unnecessary panic (Kox et al., 2015). On the other hand, as a quote in the study of Morss et al., (2015: 2021) illustrates, "waiting for clearer evidence in a rapidly evolving, highly uncertain situation costs you lead time and may even lead to a missed warning for an event". Significant uncertainty can also arise due to problems with collaborations across agencies, understanding of each other's responsibilities (Rimstad & Sollid, 2015), and interdependencies. This is particularly evident in emergencies characterized by high pressure, short time, high risk, consequences and stress (Doyle, McClure, Paton, et al., 2014: 76).

Uncertainties amongst the decision-makers

The studies analyzing the uncertainties of the decision-makers (n=8), report different types of uncertainties such as (no rank order) uncertainties related to decision-making, public reaction, communication and collaboration, ethical and economic aspects. These studies are reported in table 4 (appendix 2).

In their study regarding uncertainties in model-based decision support, Walker et al. (2003: 6) mention *decision-related uncertainties* such as how certain should one be to ban harmful activities and who should bear the responsibility of the risks of making the wrong decision. Similar issues have been raised in the study of Govaerts (2004: 33) about handling uncertainty in off-site emergency management. For example, he argues that the basic dilemma of the Three Mile Island accident, namely, how to manage uncertainties (e.g. when the reactor building is the only intact barrier) in decision-making remains unaffected. Morss et al. (2015) illustrate this with a quote coming from the interviews with one of the public officials participating in their study: "if you get it right but you waited too long, it’s not going to be as effective. But if you go too early and it turns out not to have been the disaster that you were expecting, then people will lose trust in that system” (Morss et al., 2015: 2021).

Uncertainties related to *public reactions* are also mentioned quite often. One of the respondents in the study of Morss et al. (2015: 2023) states the following: “I could stand out there with a bullhorn and say: ‘The sky is falling,’ and if no one is paying attention to me, they are going to stay in harm’s way…. The [citizens have] to help me help them”. A similar argument is brought up in the study of Fairchild, Colgrove, & Jones (2006: 961) related to decision-making and uncertainty in emergencies where they mention that such situations are always accompanied with some people who think they are "tougher than the storm". An argument related to public’s understanding was raised on the study of Cordner & Brown (2013: 484) based on in-depth interviews where a regulator states that the public does not understand that the presence of a small dose does not necessarily mean that it is harmful.

Communication and collaboration issues are brought up in the study of Kox, Lüder, & Gerhold (2018: 118) based on interviews with 27 German civil protection authorities. They argue that some of the uncertainties are associated with miscommunication and misunderstanding of the situation. This was also mentioned by Laes et al. (2005) where they mention “[…] different framing of the problem; institutional barriers; lack of communication; strategic use of scientific assessments by different stakeholders; and insufficient knowledge of scientific assessments" as types of uncertainties (Laes et al., 2005: 357). The absence of clear lines of command further complicates the response to emergencies (Fairchild et al., 2006).

The uncertainties of *ethical* nature are also often mentioned in the literature related to decision-makers. For instance, what to do with people who do not follow the recommendations regarding evacuation in an emergency as well as what to do with the sick and disabled people in such situations? It might be more harmful for them if they are moved (Fairchild et al., 2006: 964). Another kind of uncertainty of ethical nature is mentioned by Laes et al. (2005: 398) when studying the uncertainties in the nuclear policy, which is the ethical justification to continue relying on nuclear power in a perspective of sustainable development. Such issues are termed as ethical ambiguities in the literature.

Last, but not least, uncertainties of *economical* nature are mentioned by decision-makers. For instance, in the case of nuclear policy, there are uncertainties related to "the costs of decommissioning, costs of high-level waste management, but also the real costs of the business-as-usual scenario, etc.” (Laes et al., 2005: 366).

Uncertainties amongst the laypeople

The most-often-mentioned uncertainties in the articles analyzing laypeople’s uncertainties (n= 8) are related to *trustworthiness* (e.g. whom to trust) which is mostly linked to the information provider (see table 5, appendix 2). For instance, in the study of Markon et al. (2013: 320) the participants of the focus groups show high level of distrust towards the information either by stating that they can’t believe it when it comes from the government or by stating that the information given is always biased, namely in the benefit of someone who has invested in such an affair. One of the respondents in this study states this point more firmly when talking about the US five-level national alert regarding health risks: “You know for a while there was the red light, the yellow light, the blue light, and they did that so often that you couldn't care less at the end, so I don't see the purpose of that, and I think it's just propaganda, a lot of it" (Markon et al., 2013: 323).

A similar statement came from focus groups with citizens in the study of Maxim et al. (2013) where one citizen argues that she does not believe the results coming from the workers of the industry because "…they are obliged to produce results[…] and keep people calm" (Maxim et al., 2013: 685). Furthermore, in emergency situations, when there are competing messages, social media interferes making it difficult to make the difference between accurate information, rumors and malicious information (Conrado, Neville, Woodworth, & O'Riordan, 2016: 171).

Distrust towards government's actions and position resulted highest (45.2%) also in the study of Tateno & Yokoyama (2013) when analyzing the reasons of public anxiety and uncertainties related to low dose radiations based on internet surveys. Feeling uncertain and not trusting the information related to risk, proved to have an impact on respondents not changing their behavior regarding health risks (Blanchemanche, Marette, Roosen, & Verger, 2010: 287).

Laypeople also report uncertainty in the form of *emotions and feelings* such as fear, frustration, anxiety, and guilt. This can be illustrated with a quote from a study by Abbott et al. (2006: 111) interviewing citizens of Russia, Ukraine, and Belarus after Chernobyl: "It was terror. It was terror. It was scary. I did not know what to do, where to run, to go and then I was perplexed. Why did it happen like that and why was everything so calm". Uncertainty about the future is also present in the form of fear for diseases given the high mortality rates and unhealthy born children after Chernobyl (Abbott et al., 2006: 112).

Similarly, when providing the participants of focus groups with a video containing scientific uncertain information regarding endocrine disruptors, Maxim et al. (2013) found that the participants reported fear based on the negative effects of the study, although they were not certain. This fear was most of the time linked with feelings of guilt, responsibility and powerlessness, especially when having to make decisions for someone else (e.g. children) (Maxim et al., 2013: 690).

Ambiguous anxiety is also mentioned by laypeople when asked about their low dose radiation uncertainties (Tateno & Yokoyama, 2013: 14).

When asking experts on what the uncertainties of the laypeople are in their opinion, Morss et al. (2015: 2023) found that based on experts, the most important aspects that the laypeople want to know are: the nature of the hazard; where, when and how it may happen; how to receive and interpret information and what to do (and not to do) in such situations. This holds for the uncertainties related to *lack of information* as can be illustrated by a quote of one citizen: "Essentially nobody solves the Chernobyl problem. Everything is garbled because science doesn’t know how to react to it and no one cares about the people living in the zone. No one can tell us what will happen" (Abbott et al., 2006: 111). Another concern raised from focus groups with the general public is "[the] need for better, more timely, notification and general information about nuclear waste transport" (Drew et al., 2003: 266).

However, if there is ambiguous or contradictory information, this will cause further uncertainties for the laypeople. For instance, risk information that was either too specific or missed certain elements, caused *ambiguity* amongst respondents thereby making them unable to estimate the probability of the risk (Blanchemanche et al., 2010: 287). A similar issue is raised in the study of Harris (2015) related to communication of uncertainties where the media reporters argue that "sometimes scientists speak like scientists and not like people... you know, some people don’t know what low pressure means, what high pressure means, and some people don’t know and don’t care what millibars are" (Harris, 2015: 20).

Uncertainties across different study areas

The scientific community in the *radiation risk* studies, reports mainly methodological uncertainties, epistemic and aleatory uncertainties (these not being exclusive and sometimes related with each-other). These include uncertainties to low dose risks (linear no-threshold theory) in the field of radiation risk assessment (Mossman, 2009); variability among the risks posed by different nuclear power plants in the nuclear field (Bier & Lin, 2013); how to help raise public understanding of risk in the nuclear waste transportation field (Drew et al., 2003); inter-individual, spatial and temporal variabilities regarding contaminated lands (Oberg & Bergback, 2005) as well as model and parameter uncertainties in radionuclide distribution modeling (Linkov et al., 2006).

As it can be seen in table 6 (see appendix 3), more or less the same types of uncertainties are reported amongst the scientific community in other study areas as well such as *volcanic hazards* (Doyle, McClure et al., 2014; Fearnley, 2013), *flash floods* risks (Morss et al., 2015), *weather warnings* (Kox et al., 2015), *medical emergencies* (Rimstad & Sollid, 2015), etc. Such uncertainties are related to the methodological aspects such as quality, relevance and interpretation of the results (e.g. unexplained variance, reliability, random variance, etcetera (Sjoberg, 2003)); epistemic uncertainties such as the likelihood of the happening of certain events; as well as communication and decision uncertainties as to how to issue information that is subject to uncertainty, and when to issue warnings, making sure that it is neither too early nor too late.

The decision-makers in the *radiation risk research* are faced with uncertainties related to decision-making, such as how to manage uncertainties in decision-making processes (Govaerts, 2004); economic aspects such as the costs of decommissioning, nuclear waste management, etc. (Laes et al., 2005); ethical aspects related to the justification of reliance on nuclear energy in a sustainable development perspective; as well as communication aspects such as lack of communication and strategic use of the scientific assessments and information. Similar types are present in the other fields of risk research analyzed in the literature review. Apart from the above mentioned types, one type of uncertainty that was not specifically mentioned in the radiation risk research but is mentioned in other fields such as emergency evacuations (e.g. hurricanes) (Fairchild et al., 2006), emerging contaminants (Cordner & Brown, 2013), etc., is uncertainty related to public reactions. As explained earlier, this type of uncertainty deals with the public acceptance and following of the recommendations given. It is worth mentioning though, that grey literature (e.g. reports, narratives) have taken these uncertainties in consideration (Guillevic et al., 2018;

International Atomic Energy Agency (IAEA), 2016; Raskob, 2017), but they were not present in the scientific literature in which we were particularly interested on.

Similar to the previous actors, the uncertainties of the laypeople do not differ across different study areas either. Lack of trust is one of the most-often mentioned types of uncertainties both in the case of Chernobyl and Fukushima accidents (Abbott et al., 2006; Tateno & Yokoyama, 2013), as well as in other risks such as endocrine disruptors (Maxim et al., 2013). Uncertainty in the form of emotions and feelings is also mentioned in different study areas. This is mainly related to the fear of getting diseases (e.g. cancer), worry about the future and feeling guilty for the decisions made for other people. Lack of information is also reported quite often in different fields of risk research. This is linked to the need for timely, accurate and unambiguous information.

Discussion and recommendations

Our results point out that there is no scientific consensus on definitions of uncertainty. This is not entirely new as it was partly expected based on the arguments of multiple authors that uncertainty definitions are numerous and diverse (Maxim, 2014; Walker et al., 2003). However, we argue that if it is not possible to use a common/universal definition of uncertainty (given the big differences across disciplines), at least the authors/users of uncertain information have to clearly describe what they mean with the concept of uncertainty.

What came new out of our results and might serve as an explanation to this diversity in definitions of uncertainty is that only a small number of the articles define uncertainty based on its meaning. The other articles define it based on causes/sources or types and it is sometimes difficult to distinguish between these categories in trying to formulate a definition of uncertainty. For instance, lack of/incomplete knowledge is sometimes seen as a source of uncertainty (uncertainty generated due to incomplete knowledge), sometimes as a type (epistemic uncertainty) and sometimes as a definition of uncertainty itself (state of incomplete knowledge). What can be an uncertainty for a scientist (e.g. theories of low-dose radiation), can be a cause of uncertainty for decision-makers (e.g. what to take into account when assessing risks and making decisions), and as a consequence, it can result in worry or concerns amongst the laypeople (Vaiserman et al., 2018). That being said, uncertainty in knowledge can be present independently of who the user or the provider of information is. But if we look at uncertainty in communication, another explanation of this diversity of definitions can be offered. Namely, the different uncertainties between the information 'provider' and information 'receiver' (Maxim & van der Sluijs, 2011).

This led us to analyze our second research question, namely whether there are different types of uncertainties across different actors that are present in the analyzed scientific literature. Results regarding this question show us two things: *First,* the majority of the literature analyzed is focused on the uncertainties of the scientific community, while the uncertainties of the decision-makers and those of the laypeople (i.e. information receivers) are analyzed to a much lower extent. The limited attention to the latter actors also shows that research is mainly focused on the top-down communication process (information issued by scientists to other actors) when studying uncertainty communication and decision-making under it. *Second,* there are different types of uncertainty that different actors are faced with. As can be seen in table 6 (appendix 3), the uncertainty of the scientific community is more data and methodology-driven (e.g. dose-response relationships), those of the decision-makers are more related to the likely consequences of decision options and public reactions while laypeople's uncertainties are mainly related to trustworthiness of experts or the emotional potential of special risk exposure. These results do not mean that the scientific aspects of the received information are not questioned by the laypeople. On the contrary, Maxim et al. (2013: 684) found that the respondents participating in their study mentioned uncertainties regarding causal relationships, data and methodology such as limited samples, choice of variables etc. However, such uncertainties are mentioned much less in the literature related to the uncertainties of the laypeople and they are not as 'specialized' as the experts expect them to be (Maxim et al., 2013: 685).

After analyzing uncertainties across different actors, we then analyzed whether there are different types of uncertainties present in different study areas (radiation vs. other natural and man-made hazards) analyzed in the literature. The results show that the types of uncertainties present across these study areas are relatively similar and that the main difference is across actors rather than across study areas. However, we must point out that we only analyzed here articles dealing with risks such as natural and man-made hazards (articles more related to natural sciences) so we cannot come to generalizations about these results across all disciplines, such as the risks present in social sciences discipline for instance.

To explain the relevance and implications of these results for risk and uncertainty communication related to radiation protection, we need to restate the main objective and rationale behind communicating uncertainties, which is to contribute to informed decision-making amongst the receivers of the information (Doyle, McClure, Paton, et al., 2014b; Patt & Weber, 2014). To reach this objective, as our results suggest, we need to shift the attention towards knowing what kind of information is wanted and needed by the information receivers. We realize that scientific literature (articles used for this review) mainly addresses the scientific community and rarely involves risk communication directed towards general audiences. However, the main argument generated from this review is that scientific literature needs to study more the uncertainties of information receivers. This can be done empirically by using surveys, experiments, focus groups, content analysis, etc. which use information receivers as respondents. These studies would still be a part of scientific literature and communicated to other scientists. But the difference would be that they take different actors into account. Based on these results we argue that it is not about to whom these uncertainties are communicated, but rather to first understand to whom they belong. Only when we understand the uncertainties of the different actors, can we address them through communication and contribute to better decision-making.

Failure in doing so results in lack of laypeople's trust in scientists, who seem not to know the needs of laypeople, and lack of scientists' trust in the public, who seem unable to understand uncertain information (Fischhoff, 2012). This is clearly expressed in the study of Harris (2015: 20) where the scientists argued that their statements get misquoted in the media stories and that reporters are too poorly prepared, while the media reporters, on the other hand, argued that "sometimes scientists speak like scientists and not like people... some people don't know what low pressure means, what high pressure means, and some people don't know and don't care what millibars are". This means that although aiming to contribute to informed decision-making, communicating scientific uncertainties does not necessarily satisfy or decrease, the uncertainties of laypeople.

Because this work is part of a bigger project (dealing with radiological emergencies, radiological exposure situations, and decommissioning processes) we used a set of specific keywords and strict inclusion criteria to obtain articles for analysis. This made the number of articles analyzed to be rather low (33 articles) and made it impossible to take into account all literature on health effects of radiation which is scattered in a big range of disciplines. For the purpose of this study, we preferred to focus on these three cases, which are of crucial importance, and to which not too much attention has been given. However, it would be very useful that future research takes into account all literature on health effects of radiation, regardless if uncertainty is specifically mentioned in the text (which was one of the main inclusion criteria of this review). Furthermore, given that the main focus of the paper is to understand whether and how different scientific articles define uncertainty and which types of uncertainty do they mention or pay attention to, creating a new typology in order to group these definitions and types together, would be out of the scope of this review and would only add one more typology to the already vast and scattered pile of the existing ones.

Recommendations for radiation protection community

While most focus in the radiation protection literature is paid to the technical uncertainties, the uncertainties of the laypeople are much more overlooked. Consequently, research is mainly focused on the top-down communication process (information issued by radiation protection experts to other actors) when communicating about and deciding on radiation protection issues. Based on these findings, we provide some preliminary recommendations regarding both, research on uncertainty related to radiation protection, as well as, communication practices.

- Uncertainties in radiation protection research and practice need to be admitted and communicated. They should be clearly mentioned in printed format (e.g. scientific articles, newspapers, etcetera), online (e.g. information available on internet, different websites, online media of platforms), broadcast (uncertainties or limitations should not be excluded when communicating information through the media) and verbal conversations between information providers (e.g. radiation protection experts) and information receivers (e.g. laypeople and decision-makers).

1.

- The radiation protection community needs to take into account the uncertainties of the information receivers. Uncertainty assessors and/or uncertainty communicators need to be attentive to the characteristics of the target audience in order to address their fears and concerns. This means that different levels of knowledge, expertise and familiarity with terminology needs to be taken into account.

2.

- The uncertainties of the information receivers themselves, as well as their relationship to what is being communicated (e.g. is there an emotional link such as fear of cancer from low dose radiation) need to be further investigated and addressed.

3.

- Uncertainty assessors (e.g. radiation protection experts) and/or uncertainty communicators (risk management experts, medical personnel, communicators acting on behalf of the institutions/organizations) need to clearly communicate about uncertainty, its source (i.e. why is there lack of/insufficient/ambiguous knowledge), and magnitude (e.g. is it a small imprecision or a large gap in knowledge).

4.

- Uncertainty needs to be clearly explained. This can be done in different formats such as: numerically, verbally or by means of visualization.

Conclusions

After analyzing 33 scientific articles based on a selected set of keywords, directly or indirectly related to radiation risks, we found that there is no common agreement regarding uncertainty definition and these definitions differ across studies. Furthermore, we found that different actors are faced with different types of uncertainty. While the uncertainties of the scientists are more related to methodologies and results, those of the decision-makers are related to decision-making issues, public reactions and economic issues, and the uncertainties of the laypeople are related to lack of trust, lack of information and appear in the form of emotions and feelings. What's more, we found that the majority of the articles focus on the uncertainties of the scientific community while those of the decision-makers and the laypeople are taken much less into account. While this finding is not entirely new, it deserves more discussion in the radiation protection community.

Based on these findings we argue that before proceeding with communication processes, we need to acknowledge the fact that uncertainties diverge (and potentially broaden) from scientists to decision-makers and finally to the laypeople. In a two-way communication process, we have to speak each other's language for the communication to be successful. Given that the main goal of uncertainty communication is to get the public to understand, trust and make proper use of the information provided with, more attention needs to be paid to the side of information receivers (in this case decision-makers and laypeople) in order to understand what information they want and need to make informed decisions. When the scientific uncertainties of the radiation meet the very different uncertainties of everyday life, the scientific logic diverges, creating deep problems regarding communication and understanding. This is relevant not only about the nuclear or radiation aspects, but also about how scientific knowledge is constructed and communicated in general (Morris-Suzuki, 2014). Similar to risk (Renn, 2004), we argue that to bridge this gap of different perception and definition of uncertainty between different actors, two-way communication has to be initiated between scientists, decision-makers and the laypeople. This would help in offering different perspectives, create mutual understanding as well as build trust amongst the actors.

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Appendix 1: Definition of uncertainty

Table 2. Definitions and typologies of uncertainty

Article:	*Definition/Typology:*	*Reference made to:*	*Uncertainty defined based on:*	*Study focus/relevant keywords:*	*Journal:*
Bier and Lin, 2013	*"... **state-of-knowledge uncertainty** is generally taken to include those uncertainties that are reducible by further research. By contrast, **variability** reflects differences among the members of a heterogeneous population. Thus, variability cannot be reduced by research alone, but only by actually changing the circumstances for one or more members of that" (p.1900).*	Kaplan (1983)	Types	Uncertainty treatment in risk assessments	Risk Analysis
Doyle, McClure et al. 2014	*"The **epistemic uncertainty** (the unknowns) and the **aleatoric uncertainty** (the stochastic variability) of the volcanic physical process thus contributes to considerable uncertainty in the crisis management process itself"* (p.76).	/	Types	Uncertainty in Disaster Risk Reduction decision-making	International Journal of Disaster Risk Reduction
Eiser et al., 2012	*"Is uncertainty merely a state of mind—a reflection of our own incomplete knowledge (i.e. **epistemic uncertainty**)—or intrinsic to the nature of the very things about which we seek knowledge (i.e. **aleatory uncertainty**)?"* (p.7).	Bernoulli (1954)	Types	Risk, Hazard, Decision	International Journal of Disaster Risk Reduction
Fearnley, 2013	"State of incomplete knowledge: complex, non-linear, open systems" (p.1899)	/	Meaning	Risk, uncertainty, decision making, volcano alert levels	Environment and Planning A
French, 2017	*"We shall use the term **deep uncertainty** to refer to circumstances in which some uncertainties are so great that it is impossible to agree on probabilities for these" (p.3).*	/	Types	Crisis response; risk communication; spatiotemporal uncertainty	Risk Analysis

Article:	Definition/Typology:	Reference made to:	Uncertainty defined based on:	Study focus/relevant keywords:	Journal:
Han, 2012	*"...I define uncertainty as the subjective consciousness of ignorance.... Uncertainty is a "metacognition"—a thinking about thinking—characterized by self-awareness of incomplete knowledge about some aspect of the world...Three principal sources of this uncertainty can be distinguished: (a) probability, (b) ambiguity, and (c) complexity.* ***Probability*** *(otherwise known as "risk") refers to the fundamental indeterminacy or randomness of future outcomes and has also been termed "aleatory" or first-order uncertainty...* ***Ambiguity*** *refers to the lack of reliability, credibility, or adequacy of information about probability and is also known as "epistemic" or "second-order" uncertainty...* ***Complexity*** *refers to features of risk information that make it difficult to understand."* (p.165).	Smithson (1989); (Han, Klein, & Arora, 2011)	Meaning; Causes/sources	Uncertainty, probability, ambiguity, communication	Medical Care Research and Review
Harris, 2015	*"By scientific definition,* ***uncertainty implies ignorance****" (p.30).*	/	Meaning	Forecast, Uncertainty, Communication	Bulletin of Volcanology
Knoblauch 2017	*"Literature commonly distinguishes between epistemic and aleatory uncertainty.* ***Epistemic uncertainty*** *is knowledge based and is reducible with gain of new knowledge.* ***Aleatory uncertainty*** *is stochastic and irreducible"* (p.3).	(International Risk Governance Council (IRGC) (2005))	Types	Low-Probability High-Consequence Risk and uncertainty communication	Risk Analysis
Kox, Gerhold et al., 2015	*"Uncertainty arises from the stochastic variability in observable phenomena (****aleatory uncertainty****)... [and] from the lack of knowledge or incomplete observations (****epistemic uncertainty****)... Since some rare events happen unexpectedly,... incalculable* ***epistemic uncertainty is always part of aleatory uncertainty.*** *This missing knowledge leads to uncertainty about the uncertainty or "second-order uncertainty" and is called* ***ambiguity*** *or* ***vagueness*** *(p.2).*	(NRC, 2006; Pate-Cornell, 1996; Ellsberg, 1961; Colyvan, 2008).	Sources; Types	Uncertainty communication; Uncertainty perception; Emergency services	Atmospheric Research

Article:	Definition/Typology:	Reference made to:	Uncertainty defined based on:	Study focus/relevant keywords:	Journal:
Laes et al., 2005	***Cognitive uncertainty:*** *may be generated as the understanding of phenomena becomes even more complex, and... principal limits of knowledge emerge. This is often called the "problem of expertise".* ***Normative uncertainty:*** *It might be unclear which values are at stake for different social actors or the public at large.* ***Pragmatic uncertainty:*** *Results from the difficulties encountered in policy-making processes to reach conclusions and to implement decisions in a turbulent social environment* (p.358).	/	Sources; Types	Uncertainty and inequality in nuclear policy	The Journal of Enterprise Information Management
Levin et al., 2004	***Contentual uncertainty indicators****: when uncertainty is indicated by the way in which the propositional content is expressed.* ***Epistemic uncertainty indicators****: e.g. "has been considered by some,'' ''it is generally believed,'' and ''it appears that''.* ***Inferential uncertainty indicators****: when it is uncertain whether p implies q. Hence, q cannot be inferred without qualification.* ***Conditionalising uncertainty indicator:*** *e.g. hepatic tumors induced by TCE are said to be species-specific for mice and not relevant for humans* (p. 36).	/	Indicators	Regulatory toxicology; Risk assessment; Risk management; Scientific uncertainty; Uncertainty indicator; Uncertainty	Regulatory Toxicology and Pharmacology
Levin, 2006	*"The source of uncertainty is lack of knowledge, but lack of knowledge in itself does not imply uncertainty...* ***Outcome uncertainty*** *is uncertainty about propositions whose truth-value is non-determinate, as in the case of many statements about the future...* ***Evidential uncertainty*** *is due to lack of evidence for asserting a proposition"* (p. 837).	/	Sources; Types	Reporting Uncertainty in Chemical Risk Assessments	Human and Ecological Risk Assessment

Article:	Definition/Typology:	Reference made to:	Uncertainty defined based on:	Study focus/relevant keywords:	Journal:
Markon, Crowe et al., 2013	*"... **Ontological uncertainty** refers to the inherent complexity of an issue or the chaotic relationships between the elements of a system. In contrast, **epistemic uncertainty** refers to the absence or lack of knowledge about an issue. Finally, **ambiguity** is present when a situation can be interpreted in multiple ways or when there are divergences or contested perspectives about its meaning*" (p. 314).	Klinke and Renn (2002); Van Asselt and Rotmans (2002); Walker et al. (2003); Brugnach et al. (2008)	Types	Uncertainty; risk; risk communication	Health, Risk & Society
Maxim, 2014	*"...we adopted a broad, inclusive definition of uncertainty, which goes beyond mere lack of knowledge to include the following dimensions: **Technical:** includes technical errors caused by imprecise instruments or measurement methods. **Methodological:** includes whether and how researchers (a) use the best available scientific knowledge and practices in drafting the research protocol, (b) make assumptions when knowledge is lacking, and (c) choose among several available methods for assessing a parameter. **Normative**: includes interpretation of raw data and conclusions about the level of evidence they provide. **Communication:** includes how completely and understandably the research is reported." (p.7)*	Funtowicz & Rawetz, 1990	Types	Uncertainty analysis in chemical risk exposures	International Journal of Environmental Health Research
Maxim, Mansier et al., 2013	*"Uncertainty refers to a situation in which the body of evidence to arise from scientific research is perceived to be inconclusive... Even if (good) knowledge exists on a particular issue, an individual who is not aware of its existence might well feel uncertain about that issue... We distinguish **'expressed'** uncertainty from **'perceived'** uncertainty, based on the assumption that the scientific message transforms as it is communicated from the emitter (i.e. the scientist) to the receiver (i.e. laypeople)* (p. 679-680).	Brashers (2001); Powell et al. (2007);	Meaning; Types	Uncertainty; communication; risk communication	Journal of Risk Research

Article:	Definition/Typology:	Reference made to:	Uncertainty defined based on:	Study focus/relevant keywords:	Journal:
Morris-Suzuki, 2014	***'Uncertainty'** is the situation where the broad parameters of a risk are understood but science is not (yet) capable of accurately assessing the odds... In a situation of uncertainty, we are aware that there are variables we cannot predict; but in a situation of **ignorance**, we do not know what it is that we don't know (p. 349).*	Wynne (1992)	Meaning	Uncertainty in Chernobyl and Fukushima disasters	Science, Technology & Society
Romao and Pauperio, 2016	***Epistemic uncertainty**: knowledge-related issues. **Aleatoric uncertainty**: uncertainty resulting from another category of factors which are generally found to be associated with randomness. **Linguistic uncertainty**: arising from vague and context dependent terms or expressions which can impair our understanding about what is being described. **Decision uncertainty:** occurs in a decision-making process based on the interpretation of results that were expressed and communicated following a given analysis (p.4).*	Finkel (1990)	Sources; Types	Loss data; Disaster; Uncertainty	Natural Hazards
Thompson, 2002	*"Uncertainty differs significantly from variability. Uncertainty arises from our lack of perfect knowledge, and it may be related to the model used to characterize the risk, the parameters used to provide values for the model, or both. In some cases, we can reduce uncertainty by obtaining better information, but this may not always be possible"* (p.648).	/	Causes/sources (e.g. lack of knowledge); types (e.g. model and parameter uncertainty)	Variability; uncertainty; risk communication	Risk Analysis
Walker et al., 2003	*"...any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system"(p.8)*	/	Meaning	Uncertainty; model-based decision support	Integrated Assessment

Appendix 2: Uncertainties across different actors

Table 3: Characteristics of the studies and examples of uncertainties of scientific community.

Article	*Method*	*Respondent*	*N*	*Scientific focus/ relevant keywords*	*Examples of uncertainty*	*By whom is the uncertainty mentioned?*	*Journal*
Bier and Lin, 2013	Unclear	/	/	Uncertainty treatment and communication for decision-making about risk	"...there may be variability among the risks posed by different nuclear power plants, state-of-knowledge uncertainty about the average risk in a population of similar power plants, and also state-of-knowledge uncertainty about the risk at any particular power plant in that population" (p. 1900).	By the author in reference to scientists and experts.	Risk Analysis
Cordner and Brown, 2013	In-depth interviews	**Scientists**, regulators, activists, industry representatives and fire safety experts	116	emerging contaminants; ethics; risk and uncertainty; sociology of science.	"We identify four sources of ethical concerns relevant to scientific uncertainty: 1) choosing research questions or methods, 2) interpreting scientific results, 3) communicating results to multiple publics, and 4) applying results for policy making" (p. 469).	Summary of uncertainties based on the quotes of the respondents	Sociological Forum
Doyle, McClure et al., 2013	Online survey	Individuals in organizations from the natural hazard, physical and social science community in New Zealand, and from emergency management and civil defense authorities.	Various	Uncertainty in Disaster Risk Reduction Decision-making	"Considerable uncertainty can arise in the management of an event due to problems with inter-agency communications, collaborations, and the understanding of each-others' roles, responsibilities, and inter-dependencies, particularly when under high pressure, short time situations characterized by high ensuing risk and stress" (p. 76).	By the author in reference to scientists and experts.	International Journal of Disaster Risk Reduction
Drew, Grace et al., 2003	Focus groups, intake surveys and literature reviews	**Scientists**, regulators, public.	Various	Nuclear waste transportation	"Need for better education to promote lay understanding of the differences between uncertainty and variability in data to help raise public understanding of risk" (p. 266).	Quotes from the scientists as respondents	Environmental Health Perspectives
Eiser, Bostrom et al., 2012	Literature review	/	/	Risk interpretation and decision-making under uncertainty	Uncertainty over the likelihood of an event and over the value of the consequences... because 'value' means many things (p. 7).	By the author in reference to scientists and experts.	International Journal of Disaster Risk Reduction

Fearnley, 2013	Semi-structured interviews and document analysis	Scientists within the Volcano Hazard Program	93	Volcano alert levels; risk; uncertainty	"There is a clear dilemma between scientists' desire to remain neutral and report on the scientific information only, which is their area of expertise, and the importance of providing information on hazard and risk, which is regarded by many to be an essential component of a warning system" (p. 1906).	Summary of uncertainties based on the quotes of respondents	Environment and Planning A
Han, 2012	Literature review	/	/	Uncertainty, probability, ambiguity, communication	"... Exactly what are we communicating?... How should we communicate these uncertainties?... Why should we communicate [them], and what are the consequences of doing so?" (p. 155)	By the author in reference to scientists and experts.	Medical Care Research and Review
Kox, Gerhald et al., 2015	Online survey	Members of emergency services (e.g. firefighters, police officers and civil servants)	161	Perception and use of uncertainty by emergency services	"a) short warning lead times, which do not correspond with the users' needs, b) too many warnings, which may result in a dulling or crying wolf effect, c) mis-interpretation of weather information, d) dealing with uncertainty in warnings... (p. 64).	Summary of uncertainties by the author based on respondents' answers	Atmospheric Research
Kunz, Gret-Regamey et al., 2011	Expert survey	Natural hazards experts	34	Natural hazards, Uncertainties, Visualization	"...uncertainty... consists of the components of data quality as well as key elements from intelligence information assessment (p. 1737).	By the author in reference to scientists and experts	Natural Hazards
Levin, Hansson et al., 2004	Content analysis		/	Regulatory toxicology; Risk assessment; Risk management; Scientific uncertainty; Uncertainty indicator; Uncertainty	"Scientific uncertainty can be related to the study methods, i.e., to the quality and relevance of the study design, the way the study is performed, and how the results are reported. Additional scientific uncertainties pertaining to extrapolations and data gaps are added in the risk assessment process" (p. 33).	By the author in reference to scientists	Regulatory Toxicology and Pharmacology
Linkov, Carini et al., 2006	Model intercomparison	/	/	Adressing model uncertainty by model intercomparisons	"Model uncertainty seems therefore to be much greater than parameter uncertainty..." (p. 136).	By the authors	Science of the Total Environment
Morss, Demuth et al., 2015	Interviews	**Forecasters**, public officials, and media broadcasters	20	Flash flood risks and warning decisions under uncertainty	"uncertainty in monitoring and predicting flash floods" (p. 2018); "... waiting for clearer evidence in a rapidly evolving, highly uncertain situation costs you time and may even lead to a	Quotes of the forecasters as respondents	Risk Analysis

					missed warning for an event" (p. 2021)		
Mossman, 2009	Unclear	/	/	Radiological risk assessment	Uncertainty to low dose risks (example of linear no threshold theory) (p. 104).	By the author in reference to scientists and experts.	Health Physics
Oberg and Berback, 2005	Literature review	/	/	Exposure assessment; risk analysis; uncertainty; variability	"... uncertainty in model structure, parameter estimates and exposure scenarios" (p. 215); "Inter-individual variability (natural variation between individuals); Spatial variability (variations in space); Temporal variability (variation over time)" (p. 216).	By the author in reference to scientific uncertainty	Journal of Soils and Sediments
Rimstad and Sollid, 2015	Participating observation, interviews and analysis of radio communication records of medical staff	Medical emergency staff	8	Uncertainties and decision-making of emergency medical services	"... uncertainty regarding their command roles and how these were to be conducted in the best way"; "Personnel safety was a continuing uncertainty for the duration of the emergency response... it was unclear what had happened and what safety issues might be present..." (p. 4).	Summary of uncertainties by the author based on respondents' answers	International Journal of Emergency Medicine

Table 4. Characteristics of the studies and examples of uncertainties of decision-makers.

Article	*Method*	*Respondent*	*N*	*Scientific focus/ relevant keywords*	*Examples of uncertainty*	*By whom is the uncertainty mentioned?*	*Journal*
Morss, Demuth et al. 2015	Interviews	Forecasters, **public officials**, and media broadcasters	20	Flash flood risks and warning decisions under uncertainty	"I could stand out there with a bullhorn and say, 'The sky is falling,' and if no one is paying attention to me, they are going to stay in harm's way.... The population has to help me help them (p. 2023)" .	Quote from interviews with public officials	Risk Analysis
Cordner and Brown 2013	In-depth interviews	Scientists, **regulators**, activists, industry representatives and fire safety experts	116	emerging contaminants; ethics; risk and uncertainty; sociology of science.	"They [the public] just don't understand that a tiny [dose] doesn't necessarily mean harm'" (p. 484).	Quote by a regulator	Sociological Forum
Fairchild, Colgrove et al. 2006	Case study-Hurricane Katrina	/	/	Decision-making and uncertainty in mandatory evacuation in disasters and emergencies.	"Evacuations also pose special risks to the ill and disabled... whether they were harming them more by moving them or not" (p. 964).	By the author referring to public health officials	Health Affairs

Article	Method	Respondent	N	Scientific focus/ relevant keywords	Examples of uncertainty	By whom is the uncertainty mentioned?	Journal
Drew, Grace et al. 2003	Focus groups, intake surveys and literature reviews	Scientists, **regulators**, public.	Various numbers	Nuclear waste transportation	"Emergency response infrastructure is inadequate and underfunded. Need for better and more comprehensive emergency response training, especially in rural areas and within tribal communities" (p. 266).	Summary of uncertainties by the author based on respondents' answers	Environmental Health Perspectives
Kox, Luder et al. (2018)	Interviews	German civil protection authorities	27	Emergency services; Forecast uncertainty;	"Epistemic concerns such as the intensity of an event, the extent of impacts, and the warning response; miscommunication; misunderstanding of the situation" (p. 118).	By the author referring to civil protection authorities.	International Journal of Disaster Risk Science
Laes, D'haeseleer et al. (2005)	Case study- the phasing out of Belgian nuclear power plants	/	/	Uncertainties and inequalities in nuclear policy	"... lack of data; different perceptions of relevant time scales; different framing of the problem; institutional barriers; lack of communication; strategic use of scientific assessments by different stakeholders... (p. 357). "costs of decommissioning, costs of high-level waste management–all 'great unknowns'" (p. 366).	By the author referring to policy-makers	The Journal of Enterprise Information Management
Walker, Harremoes et al. (2003)	Conceptual paper	/	/	Uncertainty; Ignorance; Model-based decision support;	"What level of certainty is demanded to curtail or even ban an activity that might be harmful? Who should run the risks associated with making the wrong decision?" (p. 6).	By the author referring to policy decision-makers.	Integrated Assessment

Table 5. Characteristics of the studies and examples of uncertainties of the laypeople.

Article	*Method*	*Respondent*	*N*	*Scientific focus/ relevant keywords*	*Examples of uncertainty*	*By whom is the uncertainty mentioned?*	*Journal*
Abbott et al., 2006	Interviews, focus group and essays.	Members of the public from different socio-economic background including high school pupils and health experts.	/	Nuclear accident; risk society	"[…] uncertainty about whether they are contaminated, and they have to take hazardous decisions about where to go and what to eat. Fear, rumours and experts compete in supplying information to residents about the actual and potential consequences of the disaster, but there is little trust in, and only limited awareness of, the information that is provided (p. 105).	Summary of uncertainties by the author based on respondents' answers	Health, Risk & Society
Blanchemanche, Marette et al., 2010	Experiment	Households	200	Uncertainty transfer from risk assessment to public	"... Women feel uncertain about the risk and are not confident that they are really at risk; therefore, they do not change their consumption behavior (p. 287).	Summary of uncertainties by the author based on quotes of the respondents;	Health, Risk & Society
Conrado, Neville et al., 2016	Method framework			Social media uncertainty in decision-making during emergencies	"... message and source uncertainty... it is not always possible to know if messages are accurate, rumours or even malicious" (p. 171).	By the author when referring to citizens.	Journal of Decision Systems
Drew, Grace et al., 2003	Focus groups, intake surveys and literature reviews	Scientists, regulators, **public.**	Various	Nuclear waste transportation	"Need for better, more timely, notification and general information about nuclear waste transport" (p. 266).	Summary of the uncertainties by the author based on respondents' answers	Environmental Health Perspectives
Markon, Crowe et al., 2013	Focus groups and interviews	Adults	47	Uncertainty; risk; risk communication; risk perception; qualitative analysis	"We have to read everything, you look at the government, the people are supposed to be helping us, and they give us something, and we say, I can't trust you" (p. 320).	By one respondent in the study	Health, Risk & Society
Maxim, Mansier et al., 2013	Focus groups	Laypeople	Various	Uncertainty; communication; endocrine disrupter; controversy; risk communication	"This does not make me want to believe them, because they work for industry, we have the feeling that they are obliged to produce results. Whereas, somehow, for the other scientists, it is more 'free'; that is to say that ... [the research] is really to gather information..." (p. 685).	By the respondents in the study	Journal of Risk Research
Morss, Demuth et al., 2015	Interviews	Forecasters, public officials, and media broadcasters	20	Flash flood risks and warning decisions under uncertainty	"[…] knowing what flash floods are; where, when, and how they may occur; how to receive and interpret warning information; and what actions to take.... (p.2023).	By the experts referring to laypeople.	Risk Analysis

Tateno and Yokoyama, 2013	Survey	Japanese parents	1793	The role of mediatiors in communicating risk of exposure to low dose radiation	Distrust towards the outlook and actions of the government- 45.2%; Hotspots and unintentional intake of contaminated food- 40.8%; Uncertainty to low dose radiation- 40.7%; Lack of knowledge regarding low dose risks- 29.2%; Ambiguous anxiety without any reasons: 8%.	Summary of uncertainties by the author based on respondents' answers	Journal of Science Communication

Table 6: Uncertainties across different research fields

Actor	*Types of uncertainties in different fields*			
	Radiological risks	Article examples	Other natural and man-made risks	Article examples
Scientific community	• **Epistemic and aleatory** - LNT Theory. - Inter-individual, spatial and temporal variabilities. - Average risk of the population at a particular power plant. • **Methodological** - Parameter and model uncertainty.	Mossman, 2009; Drew et al., 2003; Linkov et al., 2006; Oberg & Mason-Renton, 2018; Bier & Lin, 2013.	• **Methodological:** - Quality, relevance and interpretation of methods and results. • **Communication:** - Issuing useful information but which is subject to deep uncertainty. • **Epistemic and aleatory:** - The likelihood of events and risks. • **Decision:** - When to release warning?	Cordner & Brown, 2013; Doyle, McClure, Paton, & Johnston, 2014; Fearnley, 2013.
Decision-makers	• **Decision** - How to manage uncertainties when making decisions? • **Economic** - Fundings, costs and trainings. • **Ethical:** - Whether it is ethically justifiable to rely on nuclear energy in a sustainable development perspective. • **Communication** - Lack of communication - Strategic use of assessments.	Govaerts, 2004; Drew et al., 2003; Laes, D'haeseleer, & Wiler, 2005	• **Decision:** - Implementing policy decisions in uncertain situations. • **Public reactions:** - Public acceptance of recommendations and information. • **Communication & Collaboration:** - Miscommunication & misunderstanding. - Absence of clear lines of command. • **Ethical:** - What to do with people that don't follow the recommendations? - Will the sick and disabled be more harmed if evacuated? • **Economic:** - Funding, costs and responsibility of paying.	Fairchild, Colgrove, & Jones, 2006; Kox, Luder, & Gerhold, 2018; Morss, Demuth, Bostrom, Lazo, & Lazrus, 2015.
Laypeople	• **Lack of trust** - Lack of trust towards information from scientists and government. • **Feelings and emotions** - Fear of getting cancer. • **Lack of information** - Need for better, more timely information.	Abbott, Wallace, & Beck, 2006; Drew et al., 2003; Tateno & Yokoyama, 2013	• **Lack of trust:** - Distrust towards information providers. - Conflicts of interest. - Accurate vs. rumors and malicious information. • **Emotions and feelings:** - Fear, anxiety and frustration - Feelings of guilt (when making decisions for others, e.g. children) • **Lack of information:** - No sufficient information fitting the needs of laypeople. • **Ambiguity:** - Hyper-specific information	Blanchemanche, Marette, Roosen, & Verger, 2010; Markon, Crowe, & Lemyre, 2013; Maxim, Mansier, & Grabar, 2013.

Chapter 3: Knowing the unknowns: Uncertainties during radiological emergencies

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Abstract

Emergency management implies making decisions under uncertainty. Though this is a truism, uncertainties faced by different actors during radiological emergencies have not been investigated as intensively as other emergencies and lack a systematic analysis during realistic conditions. Hence, the goal of this study is to identify and analyze the uncertainties that may appear during radiological emergencies. Furthermore, this research explores among which actors and at which stages of decision-making process these uncertainties appear.

For this purpose, non-participatory observation has been used during 11 nuclear or radiological emergency exercises in the period of 2017-2018 at 29 observation points in 6 countries and 1 international exercise. The observers recorded actual behavior of different actors (participants of the observed exercises) under live conditions.

Results provide valuable insights into the complex decision-making process related to actions taken for the protection of individuals and society at large during realistic exercises of a radiological emergency. Most uncertainties synthesized from our observations are related to the practical implementation of emergency actions, e.g. the potential for unexpected failure of communication tools or channels, or the inadequacy of emergency plans to cope with the real situation. A high number of uncertainties were also associated to knowledge gaps, e.g. related to the consistency of radiological assessments or the insufficient familiarity of emergency actors with the rules and procedures. The findings of this study can inspire emergency planners and other stakeholders to strengthen radiological emergency management, advance emergency response practices, and improve communication and collaboration between different actors in emergency situations.

Keywords: uncertainties, emergency management, radiological and nuclear emergencies, nuclear accident

Introduction

In March, 2011, the world was faced with one of the most severe nuclear accidents – the Daiichi nuclear accident following a tsunami in Fukushima, Japan (Perko, Prezelj, et al., 2019). After this accident, nuclear emergency plans around the world were re-visited and new decisions about protective actions were taken. Within the European Union (EU), the new Basic Safety Standards directive[4] was adopted, where detailed requirements for emergency preparedness and management were stipulated which enable a more

[4] COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.

harmonised approach in EU. The International Atomic Energy Agency's (IAEA) accident reports detail the circumstances and consequences of radiological accidents on a regular basis[5] with detailed analysis of the accident's causes, an account of the accident response, lessons learned and, where applicable, the IAEA-facilitated international assistance.

During radiological emergencies, decisions of citizens, as well as those of experts, decision makers and politicians are confronted with high uncertainty. Related concerns may include, for instance, questions such as: *Is information of authorities trustworthy?* (Kohzaki et al., 2015; Yasumura et al., 2012); *Is my child safe at school?* (Turcanu, Perko, et al., 2020); *Is consumption of food products from the affected area safe?* (Perko et al., 2014); *Will I be able to sell food products from the affected area?* (Wolf et al., 2020); *What kind of protective measures will a neighbouring country take?* (Perko, Martell, et al., 2020)*; Are our dispersion models right or will wind direction chang*e? (De Meutter, 2018); *Shall I stay or shall I go?* (Perko, Turcanu, et al., 2012)*;* and *Will we be able to recover?* (Schreurs, 2021).

Uncertainties are also culturally dependent. What may be a high uncertainty in one country, may have a different manifestation in another. This was demonstrated in a cross-country comparison study, where highest levels of compliance with protective measures in case of a nuclear emergency were expressed in Norway, and lowest in Spain, with Belgium in between (Turcanu, Sala, et al., 2020), showing that "whether people will follow instructions" is an uncertainty for emergency management - more in Spain than in Norway.

A retrospective analysis of uncertainties experienced during past radiological emergencies based on secondary sources (media articles, documents and reports) was done by Tomkiv et al. (Tomkiv et al., 2020). The authors recognise that most significant components of uncertainties in radiological emergency management in Japan (related to the Fukushima Daiichi nuclear accident) and in Europe (Slovenia, Norway, Belgium, France and Spain related to different radiological emergencies) are: i) contradictory information and

[5] https://www.iaea.org/topics/accident-reports (accessed on 6th of January, 2021).

communication aspects, ii) technical and measurement uncertainties, iii) societal impacts and societal framing, iv) as well as ethical aspects. Another study, based on media content analysis related to the Fukushima accident in different European countries and Russia, showed that communication about health effects of radiation (e.g. effects of low radiation doses) can lead to uncertainties in mass media reporting about a radiological emergency (Tomkiv et al., 2016). In turn, this leads to uncertainties about the interpretation of radiological measurement units by the media readers, for instance, how will readers understand 100 Becquerel/kg or 10 millisievert per year (Perko et al., 2015).

Uncertainty about the economic impact associated with an accident such as, disruption to supply chains, employment and customer demand have also been discussed by Raskob et al. (Raskob et al., 2020). In addition, stakeholder panels in several European countries, identified different decision-making uncertainties: i) uncertainties that are associated with the production of the information (external to the decision-making process), and ii) uncertainties linked with the use of information (internal to the decision-making process). Moreover, based on hypothetical scenarios the European project CONFIDENCE[6] provided guidance on communicating about uncertainties in radiological emergency management (Perko, Benighaus, et al., 2020a) and proposed special maps and legends to indicate "*How uncertain is the information*" provided by experts to decision-makers (Nagy et al., 2020).

The impact of emergency situations is not only influenced by their magnitude or unpredictability, but also by people's reaction towards them (Durand et al., 2020; Eiser et al., 2012b). Moreover, decision-making under conditions of uncertainty is influenced by people's interpretation of risks, which in turn, is "*shaped by their own experience, personal feelings and values, cultural beliefs and inter-personal and societal dynamics*" (Eiser et al., 2012a: 5). Consequently, it is of great importance to identify and analyse the uncertainties in a setting that is as close as possible to a real emergency.

[6] https://www.concert-h2020.eu/en/Concert_info/Research_projects (accessed on 2nd of February, 2021).

Most studies highlighting uncertainties in emergency management draw on retrospective analyses of past events or the discussion of hypothetical scenarios with various stakeholders. Despite their inherent limitations, exercises provide a unique opportunity to broaden the scope and to follow a variety of actors (e.g. first responders, decision-makers, members of the public) and emergency phases in real time (Anderson & Adey, 2011). Samimian-Darash (Samimian-Darash, 2016) as well as Anderson and Adey (Anderson & Adey, 2011) emphasised how scenario based exercise events help practice and at the same time enact uncertainty, leading to identification of new problems related to emergency planning. Andersson et al. (Andersson et al., 2014) focused on inter-organisational collaboration and highlighted related uncertainties, for instance concerning the roles and responsibilities of the different organisations and the lack of clear control mechanisms on how to enact collaboration in practice.

This study used naturalistic observation of emergency exercises to identify and systematically analyse uncertainties that may occur during radiological emergencies under almost realistic conditions. The paper responds to the following questions: i) which are the (causes of) uncertainties during radiological emergency situations; ii) which uncertainties appear in different stages of decision-making process; and iii) which uncertainties are present among different actors and at which stage of the decision-making process? For this purpose, the non-participatory observation method is used during 11 radiological emergency exercises at 29 observation points in six countries and during one international exercise. Since the observers recorded actual behaviour of different actors under highly realistic conditions, the results of this study provide valuable insights concerning the complexity of the decision-making process under radiological risk situations.

Theoretical insights into decision-making under uncertainty

According to the recent ‘Strategic research agenda for social sciences and humanities in radiological protection’ (Perko, Van Oudheusden, et al., 2019), it is of crucial importance that we capture the different understandings of uncertainties related to radiation risks in order to bridge the gap between different concepts of uncertainty across various actors and research fields. To address this aspect, the main goal of this paper is to *identify different (sources of) uncertainties that may influence the effectiveness of radiological emergency response*.

The concept of "uncertainty" is understood in different ways across disciplines, contexts of applications and actors concerned. In their scoping review, Hoti et al. (Hoti et al., 2020) found that there is no agreement regarding the definition of uncertainty, which is mainly defined based on its sources, types or categories rather than its meaning. Although the types of uncertainty mentioned in the literature sometimes overlap, the commonly used typology distinguishes between the *epistemic and aleatory uncertainty* (Knoblauch et al., 2018; Markon et al., 2013). *Epistemic uncertainty* is mainly related to the unknowns (Doyle, McClure, Paton, et al., 2014c) and - given that it is knowledge-based-, it can be decreased with the gain of new information (Knoblauch et al., 2018). The indicators of epistemic uncertainty are words and expressions that indicate less than full confidence in, or commitment to, the content of a statement such as 'has been considered by some', 'it is generally believed', and 'it appears that' (Levin et al., 2004: 36). *Aleatory uncertainty* is also referred to as stochastic uncertainty or natural *variability* which is random (Doyle, McClure, Paton, et al., 2014b; Maxim, 2014; Romao & Pauperio, 2016) and dependent on the nature of the things for which we seek knowledge (Eiser et al., 2012b) (e.g. wind direction). It is applicable in human and natural systems and concerning social, economic, and technological developments (Walker et al., 2003).

Other types of uncertainties mentioned in the literature include ambiguity and pragmatic uncertainty. *Ambiguity* is related to a different interpretation of a situation or wording (Renn, 2008b). It gives space for interpreting knowledge in different ways or drawing different normative conclusions from the same evidence. This includes *contentual uncertainty* (dependence of the way in which the propositional content is expressed) (Levin et al., 2004), *context-dependence* (the fact that a statement can have different meanings in different contexts) (Kox et al., 2015); *underspecificity* (when the term is not as specific as needed); *vagueness* (which arises from unspecific use of a term in a borderline-case sense)

(Kox et al., 2015) and *linguistic uncertainty* (which arises when trying to express information using non-quantitative metrics) (Romao & Pauperio, 2016). Another type mentioned in the literature is *pragmatic* uncertainty which occurs when there are difficulties faced in policy-making processes to reach conclusions and to implement decisions in complex situations. This is also present when individuals can have different interpretations of the same data due to subjective judgment or differences in values, beliefs and preferences, and therefore make decisions in different manners (Romao & Pauperio, 2016). Maxim (Maxim, 2014) further defines *technical uncertainties* as technical errors caused by imprecise instruments or measurement methods; *methodological uncertainties* which include methodological challenges; *normative uncertainties* which include interpretation of raw data and conclusions about the level of evidence they provide; as well as *communication uncertainties* which relate to how completely and understandably the research is reported (Maxim, 2014). For detailed definitions of the type of uncertainties, see Hoti et al. (Hoti et al., 2020).

In this study, we apply a broad view of the concept of uncertainty, which includes lack of reliable and unambiguous knowledge, but also the variability in interpretation of data for making or delineating judgements, the diversity of selecting and weighing decision criteria and making trade-offs and the variability of interpretations between observed reality and intended impacts. As such, some observations in this study include causes and/or consequences of uncertainties too.

While in the recent decades a lot of attention has been paid to quantifying scientific uncertainty and analyzing its magnitude in model calculations (Korsakissok et al., 2020; Leadbetter et al., 2020; Maxim & van der Sluijs, 2011), the other types of uncertainties that may occur in radiological emergency situations are less studied. In real-life situations, which are prone to high risk, severe consequences and time pressure, there could be different types of uncertainties playing a decisive role in the decision-making processes and in the development of the emergency (De Marchi, 1995; Maxim & van der Sluijs, 2011; Raskob et al., 2020). These uncertainties have been addressed under different categories and typologies, across different disciplines (De Marchi, 1995; Maxim, 2014; Romao & Pauperio, 2016) and they can manifest themselves differently across different actors (Hoti et al., 2020). For instance, De Marchi (De Marchi, 1995) distinguished between scientific, legal, moral, societal, institutional, proprietary and situational uncertainties occurring in environmental emergencies, while Maxim and Van der Sluijs (Maxim & van der Sluijs, 2011) identify three main locations of uncertainty in relation to knowledge production in environmental science for policy. The latter study classified uncertainties as being related to the content of knowledge, the process of knowledge production or the context of knowledge production. Uncertainties can manifest themselves differently across different actors. Hoti et al. (Hoti et al., 2020) show, for instance, that in the field of radiological protection, scientists tend to focus on data and model-related uncertainties (e.g. dose-response relationships); decision-makers are mostly concerned with the uncertain consequences of decision options and public reactions, while citizens' uncertainties are mainly related to the trustworthiness of experts or the impacts of specific risk exposures. Moreover, the uncertainties existing amongst and communicated by scientists and experts can be perceived differently or cause further uncertainties for decision-makers and citizens (Hoti et al., 2020; Maxim et al., 2013). For instance, scientific uncertainties about the health effects from low radiation doses may cause uncertainties about the safety of locally produced food among residents of affected areas.

There is considerable research focusing on uncertainties and decision-making in different disciplines (Bier & Lin, 2013; Conrado et al., 2016; Doyle, McClure, Paton, et al., 2014c). On the one hand, it is argued that decision-makers take time, participate in analytic and deliberative conversations before undertaking decisions (K. Anthony & Sellnow, 2016). On the other hand, many authors argue that we are constantly prone to systematic errors (i.e. representativeness, availability and anchoring biases) and affected by multiple factors such as heuristics, overconfidence and other biases in our decision-making processes (Kahneman & Tversky, 1974; Maxim, 2014; Smalley et al., 2008). Although these factors mainly apply to cognitive or affective distortions, they may also apply to perceiving or interpreting statements about uncertainty or decision-making under uncertainty.

The theoretical and conceptual background of this article is based on the context of uncertainty identification and decision-making under uncertain situations. Uncertainty has been associated with attributes such as ambiguity, complexity, unpredictability or probability (Han, 2012; Hoti et al., 2020; Maxim, 2014). Decision-making under uncertainty refers to a situation where the likelihood or the severity of the consequences (or both) are partially or completely unknown (Levin, 2006). Identifying uncertainties and developing approaches to deal with them is crucial to improve protection, health and well-being of the affected population, and to minimise disruption of daily life.

The fact that radiological emergencies are accompanied by high time pressure and stress and are prone to major consequences, makes them an important study area when it comes to uncertainties. In such situations, the costs of a neglecting uncertainties can be catastrophic (Eiser et al., 2012b) and it has long been argued that the presence of uncertainty in such emergency situations can act as a constraint to emergency response (Raskob & Duranova, 2020; Sorensen & Mileti, 1987).

Extensive research shows that uncertainty is present at different stages of decision-making under emergency situations. For instance, already in 1987, in a study reviewing decision-making in warning emergency systems, Sorensen and Mileti (Sorensen & Mileti, 1987) found that decision-making uncertainties were present in each decision-making point. Such decision-making points were: the interpretation stage (e.g. recognition of the event and hazard); the decision stage (e.g. how and when to communicate); evaluation stage (e.g. the perceived impact of the decisions made); as well as exogenous influences such as time availability, previous experiences (Sorensen & Mileti, 1987). Große (Große, 2019) identified sources of uncertainties in three different stages, namely, 1) the planning stage; 2) the decision-making stage; and 3) the direction and guidance alongside these stages. Similarly, Afifi and Weiner (Afifi & Weiner, 2004) argued that the information management process starts from the interpretation stage when uncertainty discrepancy is identified, and then continues towards evaluation stage and decision stage (Afifi & Weiner, 2006).

Drawing on the aforementioned research, in this study we distinguished five stages of information processing and decision-making in which uncertainties are likely to be present and observable in emergency exercises (see table 1). We grouped the identified uncertainties based on the adapted conceptual framework proposed by Afifi & Weiner, (2004), Große, (2019), and Sorensen & Mileti, (1987) in five stages of decision-making process. These stages are: 1) the *knowledge* stage where uncertainties that may appear are related to lack of-, incomplete or insufficient knowledge/information, e.g. about the event; 2) the *judgement* stage where actors may be unsure about the consequences of different decision options. Uncertainties here are related to the variability or diversity or prioritization of argumentation when balancing pros and cons.; 3) the *decision* phase, where actors may be unsure about how to make a decision given the available options and their advantages and disadvantages as well as the degree of controversy in prioritizing options; 4) the *implementation* stage, where uncertainties are related to practical implementation of the decisions that were made and the expectations of what impacts the implementation of management measure may have., e.g. in ways that would be feasible and most effective; and 5) the *evaluation/monitoring* stage, where uncertainties, may appear when there is discrepancy between expectations and observed results and the reasons for this discrepancy are either unknown or contested (Turcanu, Perko, et al., 2020: 148).

Table 1. Various stages of decision-making process.

Decision-making stage	**Description of the stage in which uncertainties may be present**
Knowledge	Uncertainties due to lack of-, incomplete or insufficient knowledge/information
Judgement	Uncertainties stemming from balancing the consequences of decision options. Uncertainties that may appear in this stage are related to variability, diversity, or prioritization of argumentation when balancing pros and cons.

Decision	Prioritizing which decision option to choose. Uncertainty here may be the degree of controversy in prioritizing options.
Implementation	Uncertainties related to the practical implementation of the decisions made. Uncertainties here may include the expectations of what impacts the implementation of management measure may have.
Evaluation/monitoring	Uncertainties related to the effect of the actions taken (or not taken). Uncertainties here appear when there is discrepancy between expectations and observed results and the reasons for this discrepancy are either unknown or contested.

Method

In order to observe and identify the uncertainties arising in nuclear emergencies situations, as well as their causes, this study applied non-participatory observation as a technique for systematically studying the behaviour of different actors involved in emergency management (Barner-Barry, 1986). The observation process was conducted while following the protocol described in the document "*Research design for the observational study of emergency exercises in selected CONFIDENCE countries: Guidelines for researchers*" (Perko et al., 2017).

In order to identify uncertainties related to the radiological emergency situation addressed in each exercise observed, the following research procedure was applied:

1. Development of a methodological document and research protocol;
2. Training of observers;
3. Request and issue of approval for the observations, including ethical approval;
4. Selection of observation points matching the objectives of the exercise;
5. Conducting non-participatory observations (detailed field notes were written and were classified as confidential documents);

6. Conducting additional interviews in order to clarify decisions taken during the exercise and gain a better understanding of the behavior of the exercise participants;
7. Organization of workshop for researchers in order to define an analysis protocol;
8. Preliminary analysis of the collected notes by each national research team according to the agreed procedure;
9. Analysis and coding of the field notes done individually by four independent researchers and discussed during a consensus workshop;
10. Draft report made available to those responsible for the emergency exercise in each country. Participants were encouraged to provide feedback and comment on the report;
11. A final list of uncertainties was created in agreement with all participants.

Observers, observations and observation points

In this study there were 18 observers and all of them fluent in the language spoken at the specific observation points. Observers received a training before the observation. The observation points were chosen in such a way that as many actors as possible at different locations involved in the exercises were observed. In general, participants (involved actors) were not aware of the research objectives in order not to influence the observation.

To allow as little as possible disturbance of the exercise, observers wore the indication "OBSERVER" during the observations. As non-participatory observers, the researchers observed the subjects of their study without taking an active part in the situation under scrutiny (e.g. they did not ask questions during the exercise) and took care that the disruptive effect of the observers is minimal. In fact, the effects due to the observers' presence diminished very quickly over time, as reported in other studies (Barner-Barry, 1986; Birdwhistell, 1972). The observers used a specific form to take notes of the exercise developments and took pictures of elements and situations of particular interest. After the debriefing, they were allowed to conduct short interviews with the participating actors, if deemed necessary to understand and correctly interpret the participants' actions or statements during the observed exercise. For instance, during sheltering, one employee left the shelter against instructions. During the interview after the exercise, he/she explained that "*he/she is a diabetic and he/she wanted to have something sweet with him/her as he/she was uncertain, how long they will be sheltered.*"

For this study, we observed eleven radiological exercises at 29 observation points, in six countries as well as one international exercise (see Table 2). These observations resulted in seven intermediate case reports in which (causes of) uncertainties were identified and reported based on each national and the international exercise.

Table 2. List and description of conducted observations

Country/ organizer (7)	**Exercise scenario (11)** *NPP=Nuclear Power Plant	**Type/level**	**Date**	**Observation points (29)**
Belgium	An accident in a plutonium building at a research reactor site	On-site	02/06/2017	a) Crisis centre (Federal level): management of the emergency
				b) Site emergency center
				c) Evacuation room in a building next door
	Fire at a nuclear reactor in decommissioning	On-site	25/10/2018	a) Assembly point (where evacuated employees and visitors assembled)
				b) Emergency management headquarter at the installation
				c) First responders: medical team
				d) First responders: firefighters
	An accidental release of radiation in the environment from an installation dedicated to the production of radionuclides for hospitals	Federal level	20/11/2018	a) Measurement team: Field work
				b) Federal cell: radiological evaluation cell
				c) Headquarter of the measurement team: Local coordination cell
				d) Local emergency centre in a school - coordinated by civil protection
				e) Home of a first responder: member of a measurement team during an activation by pager
Greece	Nuclear accident abroad with the radiological cloud approaching the country	National level	04/07/2018	a) Incident command centre: Decision-makers
				b) Communication cell: public information officer
				c) Experts- advisors: Supporting teams (e.g. models simulation)
OECD/ NEA	NPP accident with a cross-border	International level	24 & 25/10/2017	a) Decision-makers: nuclear safety authorities (HERCA)

	radiological release (INEX5)			
Norway	Floating Nuclear Power Plant emergency	International / country waters	11/12/2018	a) Emergency management centre
Slovak Republic	NPP accident	On-site	26/10/2017	a) Emergency response centre: decision makers
				b) Assembly point - sheltering and follow-up evacuation
	NPP accident	On-site	09/11/2017	a) Medical centre: decontamination of injured person
				b) Evacuation route
				c) Assembly point - sheltering and follow-up evacuation
				d) Emergency response centre: meeting of group leaders
				e) Debriefing point
	NPP accident	Full size on-site & off-site	25/10/2018	a) Regional Civil Protection and Crisis Management Office
				b) Check point: schoolchildren evacuation, decontamination
Slovenia	NPP accident	National level	06/06/2018	a) Emergency command centre at a nuclear safety authority
Spain	NPP accident	National level	22/03/2018	a) Crisis centre: management of the emergency
				b) Emergency room of the Nuclear Safety Council
	NPP accident	Regional level	12/04/2018	a) Operative Coordination Centre in the region

Observed actors (participants of emergency exercises)

At each of the observation points, there were different actors participating in the exercises (Table 3). For the purposes of this study, we divided these actors as adapted from Prezelj et al. (Prezelj et al., 2016) in four groups, namely, (i) emergency managers; (ii) first responders (iii); public communication officers; and (iv) representatives of the affected population.

The actors that belong to the *emergency managers* group are: members of the emergency headquarter, federal crisis centre, regulatory authorities, radiological emergency authorities as well as regional crisis staff. The *first responders* group involves actors such as the measurement team, decontamination staff, firefighters, medical team, civil protection and the police. *Public communication officers* are members of communication offices and information centres involved in crisis management, and finally, the *affected population* in these observations involved actors such as evacuated employees of a radiological installation, visitors at the installation or scientific collaborators, local communities with a radiological installation and schoolchildren.

Table 3. Groups of the observed actors (participants of the observed exercises)

Actor (participant) group	Involved participants/roles
Emergency managers	• Emergency headquarters members • Federal Crisis Centre: evaluation cell, decision cell, measurement cell • Regulatory authorities (nuclear safety, health, economy, international relations) • Nuclear emergency authorities (federal, regional and local) • Regional crisis centre staff
First responders	• Radiation measurement and sampling team • Decontamination staff • Firefighters • Medical teams • Civil protection officers • Police officers
Public communication officers	• Communication office staff • Information centre staff
Affected population	• Evacuated employees • Experts in the nuclear field • Visitors of nuclear installations • Local communities • School children

Data coding and analysis

Data coding and analysis was done by eight multidisciplinary researchers from the following research backgrounds: risk communication, risk perception, nuclear emergency management, decision-making, radiation protection and risk assessment. First, an analysis of all field notes was conducted individually by groups of four independent researchers and then discussed at a consensus workshop. The exact wording/coding of uncertainties was discussed and a common agreement was reached by the research team members. Inter-coder reliability was not quantitatively assessed. However, each disagreement was thoroughly discussed until a final agreement was reached among all eight researchers. The uncertainties were grouped in different thematic categories. For each identified uncertainty aspect, all four researchers needed to achieve an agreement concerning the category that the respective uncertainty belongs to. In the case when an agreement was not achieved, the particular uncertainty was classified as a new category. For instance, *Uncertainties related to long term effects* was found only in one case.

Specifically, an inductive approach of thematic analysis according to Braun et al. (Braun & Clarke, 2006, 2013) was applied. The inductive approach is conducted by keeping in mind potential biases that can influence the analysis such as researchers' disciplinary knowledge and expertise and prior research experiences (Braun & Clarke, 2006). Therefore, the analysis of the data in this study aimed to stay as close as possible to the real meaning of the data collected, while researchers tried to avoid biases in interpreting the data, but instead inductively created codes which then led to the categorization of different uncertainties that are present in emergency response. The thematic analysis offers space for flexibility with theoretical frameworks (Braun & Clarke, 2006, 2013), which allowed for a combination of different categories of uncertainty that were present in the literature and new categories which emerged from the collected data.

As advised by Braun and Clarke (Braun & Clarke, 2006: 16), the data analysis for this study started with data *familiarisation* (facilitated by an in-depth knowledge and engagement with the dataset), *coding* (identifying and labelling relevant features of the data based on the research question), *searching for, and reviewing themes* (created based on similar codes which were then clustered together), *defining and naming each theme*, and finally, *reporting and drawing analytic conclusions* based on the themes.

Furthermore, in the data analysis, the researchers paid attention to the construct validity for judging the quality and credibility of qualitative data. These require that special attention is given to authenticity, trustworthiness, reflexivity, particularity (treating all cases equally), subjectivity (taking into account biases), as well as triangulation across data sources (capturing and respecting multiple perspectives) (Patton, 2002). These criteria have all served as a basis of the analysis of this study.

Ethical considerations

The *European Code of Conduct for Research Integrity* (ALLEA - All European Academies, 2017) and *Research Ethics in Ethnography/Anthropology* (Iphofen, 2011) were applied to this research. To make sure that all the necessary ethical aspects of the study are addressed, we first asked for prior approval for the observations (making notes, recording and photographing) about each of the observation points to the agency responsible for the organization of the observed exercise. During and after observations, the observers took care that all notes and material collected were treated as confidential and summaries of notes were exchanged only between task members, but not distributed outside the research team. For the purpose of reporting, findings are generalized and presented in such a way that is not be possible to identify particular individuals participating in the exercises. Due to the protection of the anonymity of participating individuals, the countries in which specific uncertainties appeared are anonymized as well. This is mainly because of the specific roles and responsibilities that only a few people in the whole country have, and thus would make it very easy to identify who expressed a specific uncertainty in a particular exercise. In cases where observers took pictures, we have blurred them in order to make it impossible to identify particular participants.

Results

Which (causes of) uncertainties are identified during radiological emergency exercises?

Different dilemmas that caused uncertainties or were created by uncertainties have been observed during radiological emergency exercises. We have clustered these uncertainties into thirty-two thematic groups of uncertainties (see table 5 in appendix). During the observations we found that all types of uncertainties, such as, epistemic, aleatory, ambiguity, pragmatic, technical, communication, and other uncertainties were present in the behavior of the participants or during the communication flow among participants. In the theoretical section we explained the existing definitions of types of uncertainties. The results of this study show, however, that it is difficult to categorize the identified uncertainties into single types of uncertainties as there can be strong interrelation between them. However, an attempt to do this has been made in table 5 in appendix where we have placed the 32 thematic clusters of uncertainties under the types of uncertainties as defined in existing literature.

Uncertainty on how to decide on *protective actions* (uncertain impacts of different decision options and deciding about priorities) was the most common in all observed countries. Experts and decision makers have to deal with strong societal and political pressure when deciding on protective actions. During the observed exercises they were faced with uncertainties on what and whom to protect first, what the extent of zones with protective actions should be, how to balance the different impacts and take all societal effects into account. One of the most significant observed uncertainties here was related to how serious the accident was, leading to further uncertainties about the extent of contamination of people and environment. In order to estimate consequences, experts need to make certain assumptions, and uncertainties related to of the type of the scenarios they should base their decision on (the worst-or- the most-likely scenario) will greatly influence their assumptions. Among such uncertainties were ranking the level of emergency when often there was no insight in the number of people injured or contaminated and feasibility in implementation of protective actions for the different stakeholders involved.

The uncertainty related to the implementation of the protective actions was identified in the exercises of four countries, as well as in the international one. This refers to, among others, knowledge gaps, controversial estimates among the team and contradicting information from other sources. Specifically, the decision makers and emergency management team members wondered how specific protective actions aspects, e.g. evacuation, would be put into practice. Practicalities, such as which direction the population should be evacuated in, the starting time of the implementation of the protective actions and the resources required for the effective implementation, seemed highly uncertain. Several technical and scientific uncertainties like start time of the radiological release in the environment and radiological source term emerged as important factors during the early phase of the emergency. Uncertainty about the consistency of radiological assessment has been identified due to on-going or rapid changes in the situation, changing information about victims, lack of information about the presence of radionuclides, differences in measurement units used by different radiation measurement and sampling teams, discrepancy between simulated and pre-prepared parameters. In addition, several actors were highly uncertain about how to interpret dispersion models maps, which was often caused by the lack of explanatory information and legends on those maps.

The decisions about the affected areas and protective actions were often uncertain not only due to the scientific uncertainties related to the source term, the meteorological conditions and the model calculations, but also due to different protective actions in different (neighbouring) countries. For instance, necessary evacuation of villages/cities across the border is the responsibility of the neighbouring country. Uncertainties related to cross-border consequences as well as due to political and diplomatic issues appeared as important challenges during several of the observed exercises. For instance, there are uncertainties related to lack of knowledge about the decisions that will be taken by other countries' authorities and/or uncertainties about what other authorities would do next. Finally, the uncertainty of whether people will follow the instructions or recommendations given as expected based on the written national emergency plans, has been found in all exercises where stakeholders other than decision makers have been involved. The observation results show that there are always some obstacles hindering people from following the recommendations, making this uncertainty rather large.

The second large group of uncertainties was related to various aspects of *information exchange*. The uncertainty related to the origin of the initial information about the emergency appeared mainly in decision-making bodies and among the people responsible for public information and communication. The uncertainty related to the sufficiency of the information exchange appeared often in all countries (except Norway), as well as during the international exercise. The main causes of this uncertainty were lack of information, deficiency of communication or miscommunication. This is an epistemic uncertainty which is mainly related to "unknowns".

Several uncertainties were recognized as factors influencing information exchange. A multilingual environment, noise, communicating too fast, overload of correspondence, low trust, new templates, (not) updated points of contact, miscommunication through radio channels, missing factual data and the speed of information dissemination through social media may impact the information exchange and cause epistemic, ambiguity and/or pragmatic uncertainties. It was uncertain for all actors how information will be understood by different stakeholders. For instance, they were concerned about how media will report about the emergency, how foreigners at the location of an emergency will understand instructions, how the use of jargon and scientific language could affect lay people's behavior, whether the affected communities will understand and interpret the information the same way as experts or will all decision-makers understand the tasks the same way. The uncertainties related to information consistency were caused by a gap in time between the moment in which the emergency occurred and the moment in which emergency was declared; inconsistency in dates on templates, units, commas in numbers, inconsistent instructions for iodine tablets, inconsistent public information about the release, inconsistent information about number and status of victims. The timeliness of information was also highly uncertain and influenced, among others, by delays in information transmission, start time of the procedures, information about the situation, broken communication, (disrupted?) information flow to local decision makers (e.g. mayor). In several situations it has been observed that emergency actors forgot to inform first responders or to activate a member of a team. The uncertainty related to communication about negligible radiological impacts was pointed out only in one country.

A related group of uncertainties that emerged in the observations referred to *reliability of information communication technologies*. This can lead to aleatory (stochastic) uncertainties. These were caused by broken telecommunication, software systems, automatic warning systems, phone centres, printers, mistakes in connection between a simulator and a decision support system, malfunctions of an automatic activation system for members of an emergency team, among others. All countries observed were faced with this type of uncertainty. In addition, the communication channels were often broken or perturbed by a lot of noise, overloading of lines, bad signal or inoperative information exchange tools. This was a common observation in all countries and in the international exercise. Moreover, in many observed countries multiple actors were uncertain about which information can be made public and which information should be restricted to the emergency management team. For instance, uncertainty here may be the degree of controversy in prioritizing options. Often, restricted information has been made public to the affected population mistakenly through radio communication used by first responders (e.g. name of a victim). How public communication and information needs will be addressed effectively is an uncertainty faced mainly by public information officers and high-level emergency management actors. A great need for information by affected population in shelters and assembly points, not updated list of contact points, no direct communication, and long waiting time for the information indicated this uncertainty. Due to the time pressure during an ongoing emergency, decisions have to be taken quickly without including or processing all necessary data, since validation of results or inserting data in templates, are time consuming.

In all observed countries where many disciplines and emergency actors have been involved, huge uncertainty emerged related to *roles and responsibilities* of various involved actors. It was challenging to know the rules, roles and competences of other actors and stakeholders involved in the emergency, which different communication channels should be used and how often; communication was limited and miscommunication present. Moreover, in some situations new inexperienced people were filling in various roles, new tools had to be used and emergency preparedness and response plans were not known or not used, causing further uncertainties. The gap between legislation, plans and reality was also recognised as both an important uncertainty and a cause of further uncertainties related, for example, to new legislation and the feasibility of protective actions. Uncertainty related to systems and their preconditions for functioning has been found in few countries. It was mainly related to the communication network and internet access. Further uncertainties in an emergency may be caused by insufficient or inadequate resources, both technical and human, and decisions on how to adapt to such situations. This uncertainty relates to the scope and extent of responsibility, accountability and function pertaining to individuals and organizations when making teamwork decisions.

Finally, decision-makers, intervention teams and first respondents had to consider *social and ethical* aspects. These considerations may originate from dealing with, or communicating about, severe casualties, including deaths; decisions on whether safety measures (e.g. wearing a dosimeter) should override helping a colleague in need; attending to the needs of the emergency team (e.g. availability of food and drink; specific family arrangements of emergency responders); concerns of people requiring evacuation about how to inform their families; problems with staying in a confined space for a long time; doubts about how much information can be disclosed; potential side effects of evacuating hospitals and nursing homes; informing parents and/or getting consent for measures taken for school children; separation of families due to the need for rapid evacuation; perception of protective actions by the publics and psychological impacts such as stress or panic. These factors can lead to epistemic, decision and ambiguity-related uncertainties, among others. There were also specific uncertainties related to strategic installations such as a nuclear reactor. These uncertainties originated from inherent tensions between safety and security and were experienced mainly by first responders. For instance, it is not always clear whether security procedures (e.g. access in a facility of first respondents) can be overridden in an emergency situation. Uncertainty related to long term consequences of an emergency have been identified only in one country. This is probably due to the scenarios used in the observed exercises, which have focused on the threat of acute phases of nuclear emergencies.

Table 5 in appendix presents the types of uncertainties as defined in the theoretical background section and provides examples of uncertainties identified from the field notes of the observations. It is important to acknowledge that some of these examples are not only uncertainties *per se*, but can also be a cause and/or consequence of uncertainty.

Which (causes of) uncertainties appear during different stages of decision-making process?

Uncertainties in the *knowledge stage* are related to lack of-, incomplete or insufficient knowledge/information. Such uncertainties are exemplified by the following questions: "*how serious is the accident?"; "is information consistent?"; "is the radiological assessment consistent?"; "are all emergency actors familiar with their roles, plans and procedures" and "which areas will be affected?"*.

The *judgement* stage is mainly related to balancing the different impacts of decision options. It deals with judging and weighting the pros and cons of different options before making a decision related to it. Uncertainties on this stage are mainly related to *the "interpretation of dispersion maps"; "how to decide on protective actions";* and *"what comes first: safety or security"*.

Thirdly, the *decision* phase which is mainly related to prioritizing which option to choose and making a decision based on this choice. Uncertainties in this stage are related to decisions like *how to communicate negligible impacts; deciding on which protective actions to apply; deciding on actions that have long-term consequences;* and so on.

The fourth stage is the *implementation* stage. The uncertainties present in this stage are related to the question on how to take actions based on the decisions that we made. After judging among different options and prioritizing one of them, this stage deals with putting those decisions into practice. As can be seen in figure 1, the most uncertainties in radiological emergency exercises that were observed for this study are present in the implementation phase. Some of these uncertainties are related to *choosing reliable tools for information exchange; balancing the gap between legislation and reality; dealing with time pressure; the adequacy of the available resources; the collaboration and cooperation among all emergency actors; informing all emergency actors timely; the familiarity of all the emergency actors with the equipment*, and the like.

Finally, the *evaluation/monitoring* phase which deals with evaluating the decisions made and monitoring the effects that this decision had. Uncertainties that were observed and identified in this stage are related to the *sufficiency of the information exchange as well as the uncertainties about whether people will follow the recommendations given.*

Which (causes of) uncertainties are present among different actors and at which stage of decision-making process?

The identified uncertainties or causes of uncertainties appeared at different stages of the radiological emergencies and were faced by different actors. In figure 1, we present the uncertainties observed during exercises. The y axis indicates the different actors, and the x axis represents the different stages of the emergency exercises where uncertainties are present, each of them presented in different colors, depending on the stage, and different shades, depending on the actor. The size of the bubble indicates how many times an uncertainty was mentioned. Hence, the bigger the bubble, the more often an uncertainty was present. The numbers inside the clusters represent the different groups of uncertainties as identified in our observations. These groups are numbered according to the table below which serves as a short version of the legend of this figure. For an extended version of the legend, as well as for examples of uncertainties under each group, see table 5 in appendix.

Table 4. Groups of identified uncertainties. Legend of figure 1.

1: How to decide on protective actions?	**12: How is information understood by different stakeholders?**	**23: Is the information exchange sufficient?**
2. Which protective actions to apply?	**13: Are all emergency response actors familiar with their roles, procedures and plans?**	**24: Which factors impact information exchange?**
3: How to implement protective actions?	**14: Are the emergency actors familiar with and trained to use the equipment?**	**25: Which tools of information exchange are reliable?**
4: How to deal with time pressure?	**15: Are the available resources adequate?**	**26: Is information-communication technology reliable?**
5: How to deal with long-term consequences	**16: Are the preconditions of the functioning systems taken into account**	**27: What is the origin of the initial information related to a radiological accident?**
6: How serious is the accident?	**17: When exactly did the release begin?**	**28: Are all emergency actors informed timely?**
7: Is there a gap between legislation (including plans) and reality?	**18: Which areas will be affected?**	**29: Which information is public and which information should be restricted to the emergency management teams?**
8: How to coordinate cross-border aspects?	**19: How to interpret dispersion models maps?**	**30: How will public communication/information needs be addressed effectively?**
9: Will people follow the instructions or recommendations (concerning protective actions) given?	**20: Is radiological assessment consistent?**	**31: How to communicate negligible impacts?**
10: How will coordination and collaboration among emergency response actors be achieved?	**21: How to deal with technical aspects (e.g. source term) during the early phase of the emergency?**	**32: Are social and ethical considerations taken into account?**
11: What comes first: safety or security?	**22: Is information consistent?**	

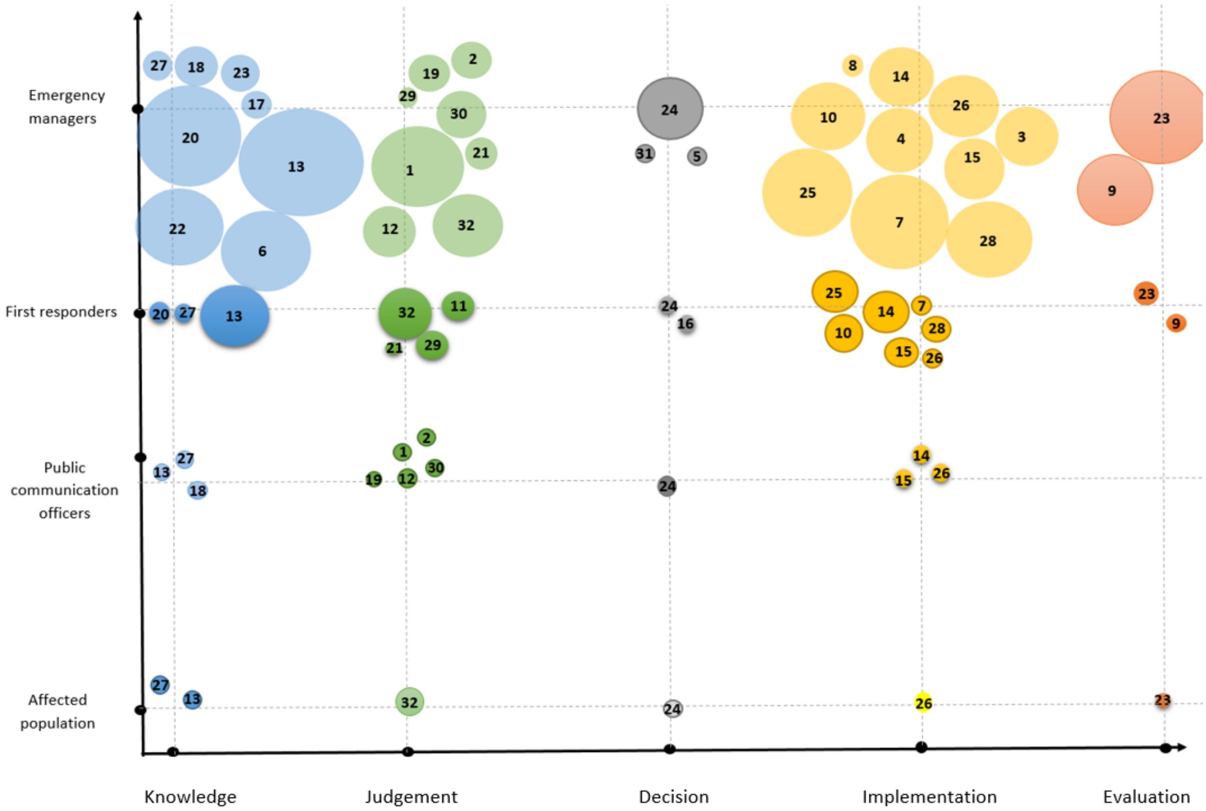

Figure 1. Uncertainties clustered across different actors and different stages of radiological emergency exercises (For an extended legend of the figure 1 see table 5 in appendix)

Emergency managers had to face a variety of uncertainties related to the consistency of radiological assessment; the implementation of protective actions; the seriousness of the accident; the familiarity of all emergency response actors with the procedures and plans; the gap between the legislation and the reality and reliability of information exchange.

The uncertainties of the first responders, on the other hand, were more related to prioritizing of safety versus security; coordination and collaboration with the other emergency response actors; the consideration of social/ethical aspects; the adequacy of the available resources, the familiarity with the use of equipment; as well as the reliability of the information exchange tools, amongst others.

The uncertainties that were mainly present amongst the public communication officers were related to the origin of the first information; the areas to be affected; the interpretation of maps; the factors influence the information exchange, the way the information is understood by different stakeholders; as well as how to address public communication/information effectively.

Lastly, although the focus of the observers has not been proportional between the affected population and other actors, we still managed to observe and identify some uncertainties of the affected population. These uncertainties are mainly related to ethical and social aspects; the origin of the first information and the sufficiency of the information exchange. In addition, the information on protective actions that affected populations received was not clear, and actions proposed were not always acceptable or practically feasible.

Discussion and conclusions

During observations of radiological emergency exercises, all types of uncertainties, such as, epistemic (Levin et al., 2004), aleatory (Maxim, 2014), ambiguity (Markon et al., 2013), pragmatic (Romao & Pauperio, 2016), technical, communication (Maxim, 2014), and other uncertainties were identified in the behavior of participants or during the communication flow among participants. Most epistemic uncertainties were related to the lack of knowledge about the beginning of the radiological release and its health effects. Weather conditions and wind direction are the most occurring aleatory uncertainties during radiological emergencies. Different interpretations and understandings of the emergency situation and protective measures were most commonly expressed uncertainties in the type of ambiguity. Implementing 'paper plans' in practice was the most common pragmatic uncertainty. Low familiarity and lack of trained personnel to use the equipment was one of many technical uncertainties. Addressing the high need for information and how to do so in a timely and clear manner were some of the communication uncertainties.

However, the results of this study show that it is difficult to categorize the identified uncertainties into single types of uncertainties as there can be strong interrelation between these different types. This finding confirms the arguments of Hoti et al. (Hoti et al., 2020) who conducted a scoping review of definitions and types of uncertainty in the radiological field. Thus, rather than placing every observed uncertainty into single types, we clustered these uncertainties into thirty-two thematic groups of uncertainties. Here, we found that not only experts, authorities and politicians but also citizens, affected in one way or another by the emergency, needed to take many decisions under high time pressure, high stakes and often lacking important information to support their personal decision. If decisions were postponed by a participant in the study, in order to wait for certainty, this waiting time often caused even more uncertainties for that participant as well as for other participants. For instance, waiting for more accurate results before issuing public information, resulted in uncertainties for the potentially affected population.

Although our observations included different scenarios (e.g. accident in floating reactor in international waters, accident at an installation producing radionuclides for hospitals and accident at nuclear power plants) in different countries, we found that (causes and/or consequences of) uncertainties were similar in all cases. While some uncertainties were clearly and easily identifiable as uncertainties (e.g. by statements such as ‘it appears that’ for epistemic uncertainty, or ‘we cannot foresee where wind will blow’ for aleatory uncertainty), there were other instances where the observed behavior or communication flow indicated also a cause or a consequence of uncertainty. This mainly depended based on who expressed a certain sentence or did something in particular. For instance, if there is delayed or incorrect information issued, then it can cause uncertainties on other actors and was reflected in some of the uncertainties, such as*, what is the origin of the first information or which information exchange tools are reliable*. As shown also in other studies, different actors are faced with different uncertainties and what can be an uncertainty for the information provider, can be a cause of uncertainty for the information receiver (Hoti et al., 2020; Maxim, 2014). Although this is truism, we could observe this phenomenon very often when delayed, biased or incorrect information is transported in the next chain in the communication sequence and this amplifies the uncertainties of other actors. This has been echoed many times in the observations. Since this increases the uncertainty over the whole communication chain, it needs to be addressed at the very early stage in order to make uncertainty more manageable and prevent its cascading through the communication chain.

Some (causes of) uncertainties that were identified, are not new for scholars of emergency management. The finding that poor communication causes uncertainties, that there are many technical and scientific uncertainties, especially related to decisions on protective measures or to models and prediction calculations, and that societal uncertainties exist, for instance related to public compliance with protective measures, are confirmed and discussed in previous research related to radiological emergencies (Durand et al., 2020; Perko, Benighaus, et al., 2020b; Raskob et al., 2020; Tomkiv et al., 2020; Turcanu, Perko, et al., 2020).

This study, for the first time, brought valuable insights related to the implementation stage of decision-making, which received most entries of uncertainties. This stage deals with putting decisions in practice. For instance, a person may know that there is an emergency going on and that authorities advice not to evacuate (knowledge/information stage); he/she evaluates the options of whether to follow the requirements regarding staying where they are or evacuating (*judgement stage*); he/she than may decide to evacuate (*decision stage*), but he/she may be unable to evacuate because the roads are blocked due to the increased traffic (*implementation stage*).

The implementation stage of the decision-making process is highly complex and affected by uncertainties due to the decisions that have been made beforehand. Many of uncertainties identified in the implementation stage may be a result of large gaps between the announced provisions and the observed reality, and/or the absence or poor implementation of planned activities in practice. This issue was emphasised in previous research which found that although well written plans exist, emergency response could still be chaotic, thereby potentially causing additional and unnecessary risks (Malesic et al., 2015; Perko & Martell, 2020; Zeleznik & Klemenc, 2015).

In addition, this research identified (causes of) uncertainties that are not mentioned neither in emergency plans, nor in scientific studies, probably because they appear to be absurd or hard to imagine. Examples of such uncertainties can be: "Are the emergency actors familiar with and trained to use the equipment (e.g. will police and firefighters understand signals and values from personal dosimeters); Are all emergency response actors familiar with their roles, procedures and plans (e.g. will newly elected mayor correctly interpret contamination maps); Are the preconditions of the functioning systems taken into account? (e.g. log books or decision support systems crashed during most of the exercises); Is information-communication technology reliable (e.g. will internet crash and will telephone alert network system work)".

There were some uncertainties identified that are specific for installations with radiological risks. For instance, "What comes first: safety or security? Or how to communicate about negligible radiological health consequences?". Extremely low doses which can be detected by sensitive equipment can be perceived as posing a high risk by some actors.

In general, these observations confirmed that the "uncertainty" was the only "certain" constant of the decision-making during radiological emergency management. Although uncertainties tend to be perceived as something negative or problematic (Brashers, 2001; Jensen, 2008) acknowledging these uncertainties can contribute to improved radiological emergency preparedness and response (Brashers, 2001; Cordner & Brown, 2013; Han, 2012; Perko, Van Oudheusden, et al., 2019; Perko, Benighaus, et al., 2020b; Raskob et al., 2020). This is particularly necessary given that in an emergency crisis, decisions and actions are often ad-hoc and reactive because the time to think, consult others or get acceptance for decisions is highly restricted (Armijos et al., 2017). Therefore, identifying, communicating and addressing these uncertainties will open the path to improve decision-making under situations of uncertainty.

The observed uncertainties can be used for improvement of emergency management in individual countries. As the exercises are performed on regular basis, it is possible to focus on identified uncertainties and to find the best solutions for their mitigation. The approaches would depend on the types of uncertainties, therefore such investigation should be performed and collected in general guides for the emergency management.

Furthermore, the observed uncertainties may also be present in other emergencies or disasters, for instance, the Covid-19 pandemic. Both emergencies require *“complex emergency management, they confront society with numerous uncertainties and may impact the functioning of society at large as well as individuals, in particular”* (Martell et al., 2021: 8). The decisions taken during both types of emergencies involve multi-dimensionality and complexity which need to address a range of various issues. For instance Martell et al., (Martell et al., 2021) argue that in order to address uncertainties, there is a need for timely and transparent communication of different views of involved actors including how and why are particular decisions taken. Another important aspect is working closely with involved actors including the affected population and those most impacted by the pandemic or the radiological emergency. This would make it easier to realize what kind of information needs to be communicated to reduce uncertainties and allow the affected population make informed decisions during the emergency (Hoti et al., 2020).

This study also has some limitations. While the main aim was to identify the uncertainties that are present across different actors and in different stages of a radiological emergency exercise, we were disproportionally focused more on emergency managers and first responders and had lower chances to focus or collect all the uncertainties that could be present among the affected population. Specific observation points were selected and this influenced the number of uncertainty items per each actor in each specific observation point. For this reason, emergency managers were observed in many more observation points than the affected population. It should be also highlighted, that the exercise scenarios were focused on the event phase of emergencies, while transition and recovery phases were not addressed.

Future research could use our classification of uncertainties to investigate the responses of actors in emergency situations that are related to actual nuclear emergencies or other technological disaster management.

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Appendix 1

Table 5: Types and examples of uncertainties as identified from field notes (Legend of figure 1)

1: How to decide on protective actions? *PRAGMATIC UNCERTAINTIES*
"The radiological evaluation cell considered sheltering unnecessary, but the decision-makers decided reflex actions (sheltering)-
"This info didn't come back to the radiological evaluation cell (also because logbook crashed).";
"What do police agents have to do if they have to set up a perimeter in the area where the irradiated winds blow?";
"What is a recommendation and what a measure?";
"They do not agree what to propose for pregnant women and children.";

“It is a political decision since there are different levels of protection in different regions although radiological risk is the same.”; *“In decision making consulting a neighbouring country should be also a criterion - Differences in different levels in different countries are the main obstacles for coordinated approach to emergency management. - Protective measures are not based only on technical but also on societal aspects. You should justify e.g. why a small village is evacuated and not a city.”;* *“There are very sharp lines here, what if I lived on the side of the street which is evacuated?”-“Are preventive measures really needed?”;* *"From the radiological point of view, there is no forecast of external leakage (decision about evacuation needs to be taken). - Is it really necessary to evacuate if there has not been any leakage? Even if there is no external leakage forecast? Perhaps we can send them home?”;* *“Are some of the measures by the regional crisis management staff just a reaction to the potential social pressure?”; “Internal discussion about the reaction or overreaction by the delegation of a government.”*
2: Which protective actions to apply? ***PRAGMATIC UNCERTAINTIES*** *“They are not sure about which measures to propose and where.”;* *“Discussion about food consumption restrictions.”;* *“Disagreement about iodine tablets – We will not have any other choice than sheltering in 20km area. - If you consider giving stable iodine you would shelter up to 30-35 km. As a neighbouring country we would give iodine to more than 120km. - What would you do if I give iodine also to this part”;* *“The need to evacuate schoolchildren is discussed. Police of the affected towns is informed. They have to decide where to move the children.”*
3: How to implement protective actions? ***PRAGMATIC, EPISTEMIC, NORMATIVE UNCERTAINTIES*** “*One of the decision makers proposed sheltering to be applied in the whole country. Disagreement on the time that sheltering must start and how it will be implemented.”;* *“Probably you cannot distinguish between children and adults. When you give it to children, you give it to adults as well. You have to make it clear that is more important for children…”;* *"Too many hands are needed, locally the challenges will be massive.”- “In Fukushima we evacuated hospitals with great human cost – that must be considered”;* *“How do you tell them to stay at work if others are indoors or evacuated?";* *“They have to solve the problem how to distribute additional pills from stores.”; “Should these tablets be consumed by the population or only be distributed?”;* *“They realized that iodine has not been distributed. Should we now bring iodine tablets in the school buses?”- “They do not know if iodine tablets have to be distributed before evacuation or not.”* *“Should the evacuation start now or we should just prepare it?“ - “How to prepare the evacuation route? Where should we take the children?”- “Is it better to have the children altogether, city B can assume the arrival of 5000 children? We cannot take so long, parents will be nervous”;*
4: How to deal with time pressure?: ***EPISTEMIC, NORMATIVE AND PRAGMATIC UNCERTAINTIES*** *“We have to make an advice based on the information that we have, although it is not updated.”- “No data available yet from measurement teams?”;* *“Expert for other emergency cell comes and asks whether there is any result from the radiological evaluation; we sit there with people waiting”- “The validation is needed and this takes time. Bilateral agreements are faster than IAEA report.”*
5: How to deal with long-term consequences? ***EPISTEMIC AND ALEATORY UNCERTAINTIES*** *“The problem is that all immediate decisions have long term consequences which makes this more challenging.”*
6: How serious is the accident? ***EPISTEMIC AND AMBIGUITY UNCERTAINTIES*** *“Are there people contaminated?”- “What was exactly the accident?”- “Were the victims contaminated?”;*

"Release probably stabilized at around 100 GBq (twice more than before): the origin of previous underestimation is identified.";

"The amount of release and the timing cannot be specified at the moment? Assumptions have to be made?";

"This is the outcome based on the 'good' scenario, not the worst-case scenario.";

"More doubts about the event declaration. Emergency protocols are consulted. - Is it possible to return to category 2 once you have declared category 3?"-"Emergency director stated that perhaps they should keep at category 3 trying to be as conservative as possible. Others stated that it seems not logic to stay in category 3 once the control from remote control panel has been established. They finally decided to return to category 2, using the analogy of what is established in the case of fire.";

"New doubts about the real number of injured."

7: Is there a gap between legislation (including plans) and reality? *PRAGMATIC, ALEATORY, VAGUENESS UNCERTAINTIES*

"This is a boat, but very complicated international laws and rules apply – many uncertainties"- "But the decisions for the radiological consequences are ours – and we will make those no matter what the diplomacy of this is.";

"People don't communicate according to standard procedures (radio communication)";

"There is another traffic accident on the way that measurement team is using. More delay.- NO PLAY information (other crisis appears)- A real crisis: protests, blockage of streets in vicinity, governor is there to negotiate with protesters, police is activated…";

"Like the police, we also see that emergency plans do not match"- "This is legislation versus reality."- "Evacuation is easier on paper than in reality, just moving that many people is a huge operation.";

"The press release was sent out without waiting for the agreement of the nuclear safety authority";

"Some part of the information is included in the emergency response plan but it is not really clear what is said."

8: How to coordinate cross-border aspects? *EPISTEMIC, CONTEXT-DEPENDENCE, VAGUENESS, LINGUISTIC, PRAGMATIC UNCERTAINTIES*

"How to implement 360^{o} radius if it includes neighboring country with other intervention levels?" - "Coordination of protective measures for populations are limited by major obstacles such as intervention levels";

"There are differences in countries response, some would start with evacuation and iodine tablets, others with sheltering and iodine tablets";

"Will neighboring country be informed before starting sirens in Emergency Planning Zone?";

"Understanding of what coordination means is an issue";

"There is a foreign ship in the country proximity. Who is responsible for emergency management in this case? The Prime minister?";

"Accident state may want to fix this themselves, how does the country judicially plan for handling this type of situation?"

9: Will people follow the instructions or recommendations (concerning protective actions) given? *NORMATIVE, AMBIGUITY, COMMUNICATION AND ALEATORY UNCERTAINTIES*

"Different cultures have to be considered. This protective action will be difficult to accept by all of them.";

"Police reports about the farmer who says "no" to evacuation. Police asks what they have to do with him.";

"Will we face mass evacuation, self-evacuation, and voluntary evacuation?";

"Although use of mobile phones and consuming food and drinks was not permitted this requirement was not followed by evacuated people.";

"A list to be signed by those who took iodine prophylaxis is circulating for signature by everybody. Nobody cares. -We will count them to know who was here instead"- "Please, attention. 4 people did not sign the list. Please, come on here and sign.";

"If it is real accident I will surely call home.";

"Call ambulance, I do not want you, no fireman, I have a pain in abdomen" - "The woman calling from the beginning ambulance is among last injured in the assembly area marked with yellow strip - light injury." - Take me to the hospital - she adjures.";

"Children coming out first are staying and chatting in a group. Do not hear the instructions; do not pay attention and listen."

10: How will coordination and collaboration among emergency response actors be achieved? *PRAGMATIC, EPISTEMIC, COMMUNICATION UNCERTAINTIES*

“Can we ask fire fighters for help?”;

"There is still no confirmation about who is ready in the measurement team. No connection established by radio or phone.”- “Why don’t you come here? - Why don’t you listen to the radio? (for this communication private phone is used)”;

"First fireman arrives: Damn it's a mess to get in and out of the site, there's nobody from the installation to show us a plan." - “Other disciplines are not present. It is a problem, we had some communication problems.”;

“They have no information regarding the discussions and the decisions made by the decision makers in Room A. Also, they do not know if anyone monitors the data from the radiological monitoring network”- “There is no communication among the members of radiation protection team.” - “The common understanding of the text of the law is not there.”;

“They decided to put a red strip on a victim - seriously injured. The yellow strip given by other first responder remained on the wrinkle. - When getting a victim to the assembly area the chief of ambulance team saying: To yellow, seeing yellow strip at the wrist. - No, to red. He/She is seriously injured” fireman said.”

11: What comes first: safety or security? *PRAGMATIC UNCERTAINTY*

“We should not have badged at the speed gate and the main entrance since we are an ambulance”- "Although I am member of the medical team I was forced to pull over for a security check.”-“Problem of rescuer identification at installation entrance: they all had to show clearance which delayed them a lot!”- “Normally a badge is obligatory, but in an emergency this may not be.”

12: How is information understood by different stakeholders? *LINGUISTIC, COMMUNICATION UNCERTAINTIES*

“After a while, a notification only in one of the national languages came on the television screen, even though there were a lot of other language-speaking people at the gathering place.”;

“Our experts were talking to local authorities in such a language that they could not understand anything.“- “How the public and technical experts interface should be discussed and improved.”;

“Are the 3 municipalities the only ones with problems?”;

“Some of employees are putting on their coats immediately, while the staff is informing loudly that that situation could last some time, may be about half an hour and there will be hot in here. They should be only prepared now, not to start evacuation.”- “Will we be surely evacuated?”;

“Regulators’ inspector speaks with regulatory body by phone. She explains the state of the emergency; she has doubts about the declared events. She consults her notes, but it seems it is not clear for her.”

13: Are all emergency response actors familiar with their roles, procedures and plans? *PRAGMATIC AND CONTENTUAL UNCERTAINTIES*

“Who communicates about protective actions?”;

“I can’t find the notification forms”;

“Who contacts the families of the injured?”- “Is there an emergency number where the family members can call?”;

“Both ask questions whether they should take the mask?”;

“What type of contamination?”;

“Can we touch the victim?”;

“Life-threatening conditions go above contamination. The nurse said she disagrees with the doctor on this. As first aiders the first lesson is our own protection first.”;

“During the debriefing, the captain said that there was not enough hierarchy.”- *"Who has to approve a helicopter flight?”- “Again discussion whether they have to go to the decontamination centre or to a hospital, they do not agree but finally decide to go to hospital”-“They do not know well how to transfer a contaminated person: Ambulance? Helicopter? How to make sure that the victim won’t contaminate the vehicles and rescuers!”;*

"After the last elections there are new representatives at the municipality (mayor, all crisis staff members) who are not aware of nuclear emergency management.";

"Emergency military unit has been activated, but they are not clear about what use they are going to make of this unit, they need authorization from the regulator."

14: Are the emergency actors familiar with and trained to use the equipment*? TECHNICAL UNCERTAINTIES*

"I don't know how to interpret this value on my personal dosemeter";

"X explains that tasks will be received via this tablet, but he can't find where. Y repeats he didn't get the training to work with this new system.";

"Call them via mobile phone – obviously they don't use XY communication channel which they should."- "Please use XY channel, you are using the wrong one.";

"They could get bigger masks. Many people did not know how to wear them.";

"The communication officer seems not to know the activation procedure for 'dark website'";

"The problem occurred with opening one storage locker as they have wrong key.";

"X has a problem with starting the computer, since he does not remember the password.";

"Problems are with registration in system 1. The problem is in a laptop that is not properly configured to be able to connect."

15: Are the available resources adequate? *PRAGMATIC AND TECHNICAL UNCERTAINTIES*

"We only have 1 oxygen cylinder. What if the 2nd victim also needs oxygen?";

"Discussion on possible ways of implementing a radiation measurements campaign - How would this be done with limited resources? What capacity does the nuclear safety authority have to go 24/7 and handle reports from all the branches who need to be/are mobilized?"-"Lack of human resources / who is going to deal with the 'dark website' content?";

"We have only one ambulance car, it takes time to return…"; "Is there anything foreseen for posttraumatic stress? Not by us, but this is important!".

16: Are the preconditions of the functioning systems taken into account? *TECHNICAL AND METHODOLOGICAL UNCERTAINTIES*

"There is a vehicle from civil protection with a satellite which is supposed to locate everybody with Wi-Fi, but it doesn't work."- "They wonder what if there is no network?"- "Communication responsible still doesn't have Wi-Fi access";

"The logbook is crashed."

17: When exactly did the release begin? *EPISTEMIC UNCERTAINTIES*

"The amount of release and the timing cannot be specified at the moment? Assumptions have to be made?"-"We do not know the exact release time."- "Misunderstanding regarding the beginning of the release."

18: Which areas will be affected? *EPISTEMIC AND ALEATORY UNCERTAINTIES*

"When will the plume arrive? – "Possibly after the midnight" – "Release time is needed for the assessment of the impact, yet we cannot estimate it."-"The person in charge says that we do not know when the plume will arrive in the country"-"Plume trajectories available – discussion on specific regions."-"I would not give the information about the arrival time."-"We would wait for a map to be precise, to check weather forecasts for identifying immediate threat - I am not sure whether our institution would be able to issue such a map in 2 hours.";

"Each country calculated the area with their own model based on the same source term. - Here there are discrepancies with different approaches. - The problem is that every country will calculate own protective actions."

19: How to interpret dispersion models maps? *NORMATIVE, CONTENTUAL, COMMUNICATION UNCERTAINTIES*

"Public relation officer (PR) asked for a copy of the maps and the measurements. A decision has been made to publish maps showing the plume. PR asked who is going to prepare explanatory notes about the maps and what extent of uncertainty we have regarding the data." ; "Problem identified in reading and understanding the maps by the decision makers provided by the experts group preparing the maps"- "The person in charge discusses with the coordinator of experts group on what info is needed to be

included in the maps"- "The experts group sends by email to decision makers the maps and doses – a lot of questions by decision makers, more clarity in the maps is asked."; "Maps are discussed, however it is not easy to understand what they depict."-"Our decision makers don't understand such scientific maps. - Decision makers need other maps."- "Important information missing: intervention doses, is it controlled release, duration of the release (it is not clear from the picture whether this is a real release or prognoses)."
20: Is radiological assessment consistent? *METHODOLOGICAL, EPISTEMIC AND ALEATORY UNCERTAINTIES* *"The doses impact is now higher that we were calculating before.";* *"Time 13:24: 'No one is left in the zone' - Time 13:32: '2 people are missing', they are not sure in which site they were. - They get informed that one of them did not come today at work and the other one 'maybe' is missing. - The operator still doesn't know who is missing.";* *"Time 13.43: the third victim is brought outside.";* *"Discussion about why one of fireman has a higher radioactive iodine dose - Expert asks to check if he was previously medically treated for thyroid problems."; "Which radionuclide is out-there? Only Iodine or Caesium as well?- We don't have this information, we have only mSV (millisieverts)"-"Different radiation measurements units used from different teams.";* *"In 6 countries we had 20 differences in dose calculations. -Even if some countries would run the models, the results would be different and uncertainties would be different.";* *"The biggest uncertainty is the source term and the weather prediction."- "Situation changes quite quickly".*
21: How to deal with technical aspects (e.g. source term) during the early phase of the emergency? *TECHNICAL UNCERTAINTIES* *"Do measurements correspond to estimations?" - "Discordance between model and measurements: model calculations used source term without Plutonium.";* *"They are not sure if they will be able to close the valve."*
22: Is information consistent? *COMMUNICATION, LINGUISTIC, VAGUENESS, UNDERSPECIFICITY UNCERTAINTIES* *"The information about base camp is not correct. Something is wrong." - "Team 2 also didn't come to the building. Coordinator is looking for them.";* *"A secretary comes in and asks for guidance regarding what should be said to the public that calls for information about the accident and required actions.";* *"Date on the template (communication to a nuclear regulatory authority) is wrong."* *"Inconsistent information that the different members of decision makers have has been identified.";* *"The head of experts group said that the meteorological data are not ok. - Doubts about how reliable the meteorological data could be.";* *"The iodine pills were ordered in other country (X) and did not fit to the leaflet information in country (Y)* *"The level of water was wrongly given in the report (1.031 instead of 10.31).";* *"Noticed that the fax includes wrong risk level, it must be corrected by the national authority.";* *"Confusion between the moment in which the accident occurs and the moment in which the accident is declared.";* *"They realized about a communication mistake: there are 2 injured, not 3.";* *"The regulator's inspector realized that the location of the contamination of the second injured is not written correctly on the whiteboard."; "Technicians doubt the exact time of evacuation activation (5 min.). Experts say this cannot happen, but also that it happens very often.";* *"Computers in helicopter crash. They needed to land and restart all equipment once more."*
23: Is the information exchange sufficient? *EPISTEMIC, NORMATIVE AND PRAGMATIC UNCERTAINTIES* *"There is no official confirmation yet about the accident."-"The situation and the conditions in the plant are not known.";*

"Information about the situation and conditions in the plant which is needed to assess the hazard for the country is limited."- "It seems that a release is possible"; *"No definite conclusion could be reached based on the available information."- "The level of expectations related to information is different at different countries.";* *"Maybe we forgot some information. Maybe some other would like to have more - one is saying yes, the other is saying no."- "Important information is missing: intervention doses (it is not clear from the picture whether is this a real release or prognosis), is it a controlled release, what was the duration of the release?"*
24: Which factors impact information exchange? *LINGUISTIC, VAGUENESS, TECHNICAL AND COMMUNICATION UNCERTAINTIES* *"Different languages used in an emergency cell. Experts are addressing experts in wrong languages. Some experts can't follow all the discussion.- One expert tries to translate to other expert in English (not enough time to translate everything)- Expert is using google translate to understand Logbook of the emergency centre.";* *"All information, radiological information is given orally, really fast and experts are trying to write down.";* *"They are trying to find the correct e-mail.";* *"We need to make sure they don't send us in the wrong direction."- "Bad radio-communication because of the siren overall in the town."; "Not all hear well as there are a lot of people around and voice coming through mask is not so loud."- "Some contaminated people did not hear well and went to the area where not contaminated people are gathered. "*
25: Which tools of information exchange are reliable? *TECHNICAL UNCERTAINTIES* *"Main functional communication channel is private phone"-"There are technical problems with communication technology."-"It was difficult to understand the message of the colleagues through the radio"- "XY tries to reach them with the radio, but they don't answer. He tries with his own mobile phone but also no answer.";* *"All telephone numbers from ministry of XY don't work. They don't know how to establish a contact with military."-"They told us that these numbers have been checked one week ago and everything was ok. Now, we cannot reach anyone.";* *"IT department informs about blackout in telephone lines and internet access.";* *"The radio is not working very well there. Did not hear well.";* *"Calling to responsible person with request to switch on sirens. Number is occupied. Courier is sent to fulfil the command."*
26: Is information-communication technology reliable? *TECHNICAL UNCERTAINTIES* *"Problem with internet connection continues."- "No connections with the emergency site? No video, no phone."- "Is there anybody who could contact somebody there to get more information?"- "No video conference established, problem to accept a video call."- "Problems with telecommunications."- "A software keeps breaking down. Maybe it's not connected properly?"- "Logbook software crashes."- "IT department reports about the problem with the telephone lines."- "The telephone centre is out of order.";* *"It is not possible to print documents."- "The display went out when prepared evaluation sheet, it has to be checked.";* *"The regional crisis management staff lost communication with the technical support centre at the nuclear installation in emergency"; "Someone realized that the SMS sent early in the morning to convene all the members in the regional crisis management staff has not reached everybody."*
27: What is the origin of the initial information related to a radiological accident? *EPISTEMIC UNCERTAINTIES* *"There is not yet any official notification/information" (source of information: internet)" - "We received only this information";* *"Bilateral notification (agreements) is faster and more useful than standard report form of IAEA.";* *"Why is there no alarm"; "Won't we be warned via mobile phone?"*
28: Are all emergency actors informed timely? *TECHNICAL AND PRAGMATIC UNCERTAINTIES* *"There is a big delay in information transmission using different communication channels to inform first responders (in this case a firefighter)"- "Results not yet at emergency response centre."- "I hope they received information that radiological evaluation cell is operational (before Logbook crashed)";*

“Is military informed about the drone for radiological measurements? It is not allowed to use drone in the nuclear domain?”;

“Discussion about time, when the information must be sent”- “Hope they arrived. They didn’t report the arrival time”;

“The nuclear installation in emergency reports that they do not receive e-mails from the national authorities.”;

“Should local mayors be informed?"

29: Which information is public and which information should be restricted to the emergency management teams? *PRAGMATIC UNCERTAINTIES*

“*How to explain to my family that I have to leave and not to disclose too much of information or increase concerns?”;*

“Are we ready to answer all questions?”- “We need to include facts and not assumptions in the press release.”

30: How will public communication/information needs be addressed effectively? *COMMUNICATION AND AMBIGUITY UNCERTAINTIES*

"The people in the shelters and assembly points would like to know what is going on outside.”;

“It is demanding to synchronize information. Information for the spokesperson is coming with delay.”;

“Contacted spokesperson of the enterprise was not in agreement with decision support system, information was supported by fax. – He had no information. - The change of person at the enterprise was not announced.”;

“Communication is the biggest uncertainty.”

31: How to communicate negligible impacts? *COMMUNICATION AND LINGUISTIC UNCERTAINTIES*

“How to report low environmental impact in case of negligible radiological doses?” – “How to explain health effects of low doses of radioactivity to population (there is no consensus on this)”.

“The national authority organization will correct their statement - The environmental impacts are negligible and without consequences for the inhabitants”;

“Preparation of press statement No 4: is the dose due to noble gases an increased environmental impact?”

32: Are social and ethical considerations taken into account? *PRAGMATIC AND EPISTEMIC UNCERTAINTIES*

“The medical team is not sure whether someone should stay with the (contaminated) body.”

”X calls his son to check whether he’s ok and ready to go to school.”- “What shall I do with my child: he needs to go to school only at 8.00 and I have to leave at 6:00? - Will I be back in time?”;

“What to say to my partner? What is going on; How much of information can I disclose?”;

“We evacuated hospitals with great human cost.”;

“Evacuated employee received a mobile call from his wife: … no, do not be afraid, you should hear an alarm if something happens… I am telling the truth, it is only an exercise.”;

“If we evacuate the children from school also parents will evacuate spontaneously.”-“What will be the reaction of the parents?”

Chapter 4: Who is willing to participate? Examining public participation intention concerning decommissioning of nuclear power plants in Belgium

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Abstract

Decommissioning of Nuclear Power Plants (NPPs) is now a pertinent energy-related matter since most of the nuclear reactors built during nuclear renaissance will soon reach the end of their operational life. Drawing on the theoretical framework based on elements of the Value-Belief-Norm theory, psychometric paradigm, deliberative theories of democracy and in the levels of participation as defined by Arnstein's ladder, this is the first large-scale study addressing the question of who is willing to participate in decommissioning-related decision-making procedures. Data for this study were collected via a large public opinion survey (N=1028) in Belgium in 2015, and were analysed using Structural Equations Modelling (SEM) as a method.

Results show that interest on the topic of decommissioning as well as radiological risk perception have direct effects on participation intention. Furthermore, we found that low trust in the nuclear industry, being ideologically leftist, having more negative attitudes towards nuclear energy, and living in the vicinity of a nuclear installation influences participation intention indirectly, through interest and risk perception. Based on these

findings we point out to some challenges that can appear in decision-making processes and some recommendations on how to prevent or solve them.

Keywords: Participation intention; decommissioning of nuclear power plants; risk perception; interest; SEM

Introduction

On February 2020, there was a public consultation organized in the municipality of Dessel in Belgium related to a new storage building for radioactive waste. Although such consultations are highly recommended (Gugliermetti & Guidi, 2009; International Atomic Energy Agency (IAEA), 2017) and/or legally binding (Richardson et al., 2013; UNECE, 1998), and although Dessel has almost 10,000 residents, the public consultation meeting attracted only 18 participants. Out of these 18 participants, only 2 of them were interested citizens, 3 were from a non-profit organization (STORA) and 1 journalist. The other ones were all either political decision-makers or experts from the nuclear field (SCK CEN; Belgoprocess; NIRAS-ONDRAF; FANC-AFCN).

Based on scientific evidence, this is not the first, nor will be the last case characterized with low public participation. Extant research shows that low public participation is an experience that many other situations that are not emergency-related have in common (European Commission, 2013; Ruostetsaari, 2017; Turcanu et al., 2014; Webb, 2013). Low participation in participatory decision-making processes can be problematic since this is often a regulatory mandate by which the public's input on matters affecting them is sought. Likewise in literature, citizen participation is portrayed as a key component in policy decision-making (Fitzgerald et al., 2016). While other research focuses on types of participation (Arnstein, 1969), how much influence or authority is granted to the participation (Fung, 2006), how to design participatory processes (Bobbio, 2019) or public participation mechanisms typologies (G. Rowe & Frewer, 2005), this article tries to answer the question of *who is willing to participate in decision-making procedures*, by combining elements of the Value-Belief-Norm (VBN) theory (Stern et al., 1999) with other theories such as psychometric paradigm (Slovic, 1993) and deliberative democracy (Cohen, 1997; Pateman, 2012) theories. In order to investigate the potential predictors to public participation intention, this paper focuses on decommissioning of nuclear power plants (NPPs) – another topic that the majority of the public might find non-urgent and/or purely technical.

After their operational time is finished, the nuclear installations must be decommissioned. This process involves removing the used fuel from the nuclear reactor, dismantling systems or components containing radioactive products (e.g., the reactor vessel); as well as cleaning up or dismantling contaminated materials from the facility (Nuclear Energy Institute (NEI), 2019). This makes the process much more expensive and time consuming for nuclear power plants than retiring other power plants (Energy Information Administration (EIA), 2017). While to most people, this would be a technical, not a social task, it actually involves many associated risks and public concerns which mainly arise as a result of the different perceptions, attitudes, opinions and concerns of stakeholders towards the risks and benefits of decommissioning programmes as well as lack of stakeholder involvement planning (Perko, Monken-Fernandes, et al., 2019). This makes decommissioning of nuclear installations a vivid example of social links to a technical task.

Public involvement in decision-making processes related to decommissioning programs is required in Europe by multiple regulations (e.g. the amended Environmental Assessment Directive 2014/52/EU, European Council Directive 2011/92/EU, and the Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters). There are various techniques and instruments explicitly designed to enhance public participation such as the organization and implementation of focus groups, expert panels or hearings, roundtables, interest groups, in-depth groups, citizen juries or panels, citizen advisory committees, consensus conferences, coercive dialogues and other public meetings (De Marchi & Ravetz, 2001; Di Nucci et al., 2017; Krütli et al., 2010; Renn, 2008b). However, a review of these instruments is out of the scope of this paper as here we want to identify who is willing to participate on decommissioning-related decision-making processes.

Public participation in decision-making procedures concerning environmental aspects in general and related to nuclear waste disposal in particular, not only gives the communities a say on the matter, but also increases the social acceptance of predefined technical solutions (Hietala & Geysmans, 2020). That being said, arguments for public involvement in decision-making procedures have an instrumental rationale which is that participation may decrease conflict and increase acceptance of or trust in the science that feeds into the environmental management process; a normative rationale which argues that the processes of environmental assessment and environmental management should be legitimate; and a substantive rationale which argues that relevant wisdom is not limited to scientific specialists and public officials but mutual learning is needed (Stern & Fineberg, 1996). The relevance of public participation in decision-making procedures has also been supported by other empirical studies (Irvin & Stansbury, 2004; Liu et al., 2019; Pölzl-Viol et al., 2018; Schroeter et al., 2016) and has been translated in the EU governance frameworks and science policy strategies such as the one about Responsible Research and Innovation (RRI) (Owen et al., 2012).

Despite all the recommendations, however, research shows that a major part of citizens are not motivated or willing to be actively involved in organized decision-making processes. For instance, a European Survey in 2013 showed that 37% of the Europeans think that public dialogue is not needed when it comes to decisions made about science and technology, whereas only 16% think that the public needs to be actively engaged (European Commission, 2013: 37). An earlier survey coming from the same institution found that only 25% of the EU population would like to be directly consulted and to participate in decision-making processes on the development of national energy strategies (European Commission, 2010). Similar results come from more recent articles too. For instance, Ruostetsaari (2017) found that when it comes to the energy policy in Finland, the citizens prefer that these decisions are made by experts. Similarly, in a study about public participation related to new nuclear research reactors Turcanu, et al. (2014) found that more than half of the respondents (57% out of N=1020) did not intend to participate at all or only wanted to receive information related to such activities. Literature concerning the recent turn to authoritarianism points out to the same issue (Heinberg & Crownshaw, 2018; Murakami Wood, 2017). For instance, Hibbing & Theiss-Morse (2002) talk about stealth democracy when arguing that public participation intention is low simply because people do not want to participate and do not like being involved in a process of openly arriving at a decision in a situation of diverse options (Hibbing & Theiss-Morse, 2002). Further, they argue that the majority of the public prefers stealth democracy because it finds decision-making and conflict uninteresting and they want the job to be done by the people who are paid for this (McHugh, 2006). Participation fatigue (Lammi, 2009; Wesselink et al., 2011), non-responsive government (Muhlberger, 2018), and lack of trust due to previous experiences where public concerns have been disregarded (Neblo et al., 2010) among others, have been found to play a role on low public participation intention.

By building on these theoretical and practical findings that (apart from protests and grass-root opposition), a major part of citizens are not willing to participate in organized decision-making process, this article attempts to find out who are those people that do or do not want to participate. In so doing, it addresses the gap in public participation in decision-making processes related to decommissioning of NPPs which is a pertinent energy-related matter since most of the world nuclear reactors built during nuclear renaissance (Goodfellow et al., 2011) will reach the end of their operational lifetime in the next years, and in Belgium, which will be the specific focus of this study, all 7 reactors will reach their operational lifetime of 40 years in the period 2015–2025, which will need to be shut down according to the law (Latré et al., 2019). Drawing on a theoretical framework based on elements of the Value-Belief-Norm theory (Stern et al., 1999), psychometric paradigm, and in the levels of participation as defined by Arnstein’s ladder (Arnstein, 1969), it is the first large scale empirical study investigating the extent to which “laypeople” wish to be involved in decommissioning-related decision-making processes. While previous research has only looked at the direct effect of the explanatory variables (Ruostetsaari, 2017;

Turcanu et al., 2014), in this study, based on elements of the VBN theory and psychometric paradigm, we also analyse the mediating effects of risk perception and interest, which also offers a methodological contribution. In addition to theoretically and methodologically contributing to studies on public participation, this study also offers valuable insights for authorities responsible for decommissioning of NPPs and public engagement practitioners in order to successfully plan required public engagement in decommissioning processes.

In the next sections, we provide a more detailed explanation of the theoretical argument based on which the hypotheses of this paper are formed. Afterwards we explain the methods and the data collection process. In the fifth section, we reveal the results of the analysis and subsequently we discuss the implications as well as the limitations of the study. The last section is a conclusion of the paper.

Theoretical argument and hypotheses

Value-belief-norm theory and its elements tested in this study

A number of models from different disciplines that explain participation intention can be found in the literature (Ajzen, 1991; Fishbein, 1980; Sheppard et al., 1988; Stern, 2000). An important theory explaining participation intention is the value-belief-norm (VBN) theory which links value theory (Dietz et al., 1998), norm-activation theory (Schwartz, 1977, 1994) and new environmental paradigm (NEP) perspective (Dunlap & Van Liere, 1978) through a causal chain of five variables leading to participation intention (see fig. 1) (Stern, 2000). When compared to these theories alone, the VBN theory proved to explain the highest variance related to participation intention on environmental-related activities (Stern et al., 1999). The theory argues that individuals who feel that salient values are affected in decisions that require public input, believe that there are some adverse consequences or threats to the objects they value, and believe that their actions can make a difference are more likely to participate (e.g. activism, public sphere support, private sphere activism, etc.) (Stern, 2000; Stern et al., 1999).

As can be seen in figure 1, the VBN theory argues that certain values have a direct effect on problem awareness, which then indirectly influences interest and participation intention. Such values can be biospheric values (reflecting an individual's care about the environment and nature), altruistic values (reflecting the extent to which people care about the others or nature), and egoistic values (whether people care about money and power) (van der Werff & Steg, 2016). Problem awareness, in the context of the VBN theory measures the extent to which people perceive something to be a threat or have adverse consequences for them, their families, their country or the nature (Stern et al., 1999). In practical terms related to decommissioning of NPPs, problem awareness is a similar measure as radiological risk perception, which measures the extent to which people perceive and evaluate risks from nuclear/radiological-related activities. For this reason, in this study we will use the term 'risk perception' instead 'problem awareness' or 'adverse consequences for valued objects' as termed by the VBN theory.

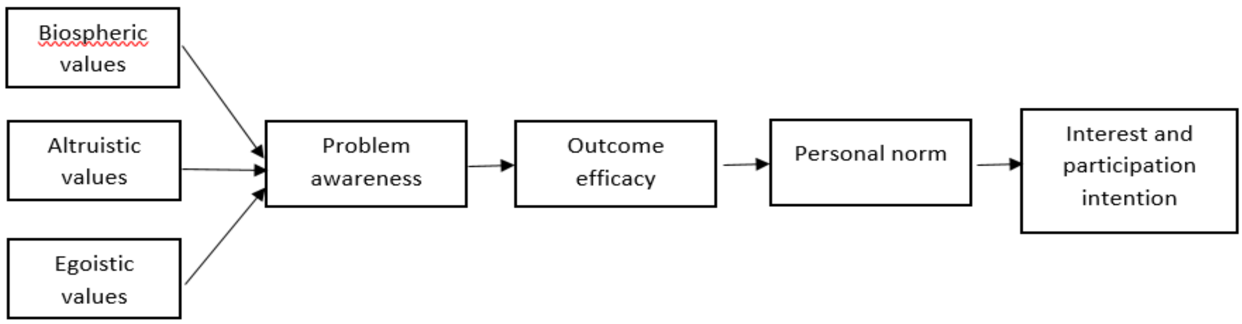

Figure 1. The Value-Belief-Norm (VBN) theory.

The following subsections describe first the independent and mediating variables that were derived from elements of the VBN theory in combination with other theories explained below; secondly they explicate the hypotheses that link these variables with the dependent variable "intention to actively participate"; and thirdly address the issue of operationalizing this independent variable using the categories of Arnstein's ladder of involvement.

Elements of risk perception theories tested in this study

Risk perception mainly denotes the mechanisms and processes of how individuals think and feel about the risks they face (Sjoberg et al., 2004; Slovic et al., 2004). In this study we focus on radiological risk perception. Studies on risk research show that radiological risk perception is not only affected by values, but also by attitudes to objects or persons related to the risk, psychometric factors relating to specific properties of the risk or the risk situation and other attributes such as political preferences (Latré et al., 2019; Perko, Železnik, et al., 2012; Wiegman & Gutteling, 1995).Such influencing variables that may explain participation intentions related to decommissioning of NPPs include trust in authorities, attitude towards nuclear energy, living in the vicinity of a nuclear installation, and ideological position. For instance, studies focusing on risk perception towards nuclear energy (Ryu et al., 2018; Slovic et al., 1991), on Genetically Modified (GM) foods (Poortinga & Pidgeon, 2005), and other risk research fields (Ibitayo & Pijawka, 1999; Lobb et al., 2007; Renn, 2008b; Siegrist et al., 2000, 2005; Viklund, 2003) found trust in regulation to have an effect on risk perception, where low trust in regulation leads to higher risk perception. Consequently, trust is proven to have a strong impact on participation intention (Muhlberger, 2018). For instance, Neblo et al. (2010) argue that only when people do not trust the process or the decision-makers, will they be more dissatisfied and feel that they have to participate themselves in the decision-making process.

Turcanu et al.(2014) found that negative attitudes towards nuclear energy were one of the strongest predictors towards public participation intention related to nuclear research installations. Perlaviciute & Steg (2015) found that this attitude can be rooted in people's values, indicating that higher biospheric values lead to more negative attitudes towards nuclear energy (when it comes to environmental consequences). However, research also shows that attitudes towards nuclear energy can negatively influence risk perception. For instance, in 2008, Renn argued that more research needs to be done in order to improve our knowledge related to the links between risk perception, attitudes towards risk objects and behaviour. Four years later, Perko et al. (2012) found that the more an individual is against nuclear energy, the higher their risk perception is. For this reason, in this study we treat attitudes towards nuclear energy as an independent variable of participation intention, which can have a direct effect, as well as an indirect one, through risk perception.

Studies concerning vicinity show that living in the vicinity of a nuclear installation can have opposing effects on participation intention depending on the mediator (Perko, Železnik, et al., 2012; Perko & Martell, 2021). For instance, several empirical studies show that people living in the vicinity of operating nuclear installations perceive lower radiological risks than the regional or national average, suggesting that familiarity with such installations reduces perceived risks (Lyons et al., 2020; Maderthaner et al., 1978; Perko, Železnik, et al., 2012; Perko & Martell, 2021; Wiegman & Gutteling, 1995), and therefore makes people less likely to participate in decision-making procedures (Hibbing & Theiss-Morse, 2002; Perko et al., 2013; Webb, 2013). On the other hand, living in the vicinity can have a positive direct effect on public participation. For instance, in post-nuclear accident issues, local actors in communities with personal experiences linked to nuclear were found to be more willing to engage in decision-making procedures (Pölzl-Viol et al., 2018) and in Slovenia a partnership approach for low and intermediate level waste was developed, which resulted in local communities that lived in vicinity of existing NPP to agree in hosting a new repository (Perko & Martell, 2020). Applying interest on the topic of decommissioning as a mediator also contributes to the opposing effect of vicinity on participation intention. For instance, living in the vicinity of a nuclear installation can increase one's interest on the topic, and therefore also increase his/her participation in decision-making procedures concerning decommissioning (Hibbing & Theiss-Morse, 2002; Neblo et al., 2010; Tommasetti et al., 2018). Finally, political preferences or ideologies are proved to influence risk perceptions as well. Several studies found that people with a left-wing political preference reported higher risk perception related to chemical plants and radioactive waste (Rothman & Lichter, 1987; Wiegman & Gutteling, 1995) and also that risk perceptions of nuclear power is 'anchored' with political ideology (Costa-Font et al., 2008). Similarly, studies in Belgium show that left-wing parties are against nuclear energy, while the right-wing ones favour it more (Latré et al., 2019; PartiRep, 2014). In this study, based on McCollom, Trice, & Beyer

(1994:33) we define ideology as "shared, relatively coherently interrelated sets of emotionally charged beliefs, values, and norms that bind some people together and help them make sense of their worlds." Similarly, Oliver & Johnston (2000:1) argue that “ideology is rooted in politics […] and points to coherent systems of ideas which provide theories of society coupled with value commitments and normative implications for promoting or resisting social change.” Studies on climate change found that left-wing individuals have stronger altruistic and biospheric values (Dietz et al., 2007; Visschers, 2018), and are more likely to embrace environmentalism (Harring et al., 2017). That is why, in this study we use left-right ideological position as a proxy for measuring altruistic and biospheric values. Furthermore, research shows that left-wing citizens (with stronger altruistic and biospheric values) are more likely to support direct democracy, while those leaning to the right prefer more stealth democracy (Bengtsson & Mattila, 2009), thus being less likely to participate in decision-making procedures. By combining the VBN theory with the other theoretical arguments mentioned above, we hypothesize that:

[H1a] Individuals that have lower trust in nuclear industry’s capacity to decommission NPPs have a higher radiological risk perception.

[H1b] Individuals that have more negative attitudes towards nuclear energy have a higher radiological risk perception.

[H1c] Individuals that live further away from a nuclear installation have a higher radiological risk perception.

[H1d] Individuals that are more ideologically leftist (biospheric values & altruistic values) have a higher radiological risk perception.

The VBN theory argues that when individuals recognize that a certain risk situation or potentially dangerous technology poses threat to other people, other species or nature (problem awareness) they are more likely to act against it. This was confirmed earlier by the norm-activation theory in the environmental-related field (Schwartz, 1977) but also in other fields such as political science (Hibbing & Theiss-Morse, 2002; Neblo et al., 2010;

Webb, 2013) and risk research (Perko et al., 2013; Turcanu et al., 2014). Similar to VBN theory, these studies argue that risk perception is a predictor of participation intention, therefore, we hypothesize that:

[H2] *People that perceive higher risks from nuclear installations are more likely to participate in decision-making regarding decommissioning of NPPs.*

[H2a] *Risk perception will serve as a mediator between the explanatory variables as expected by hypotheses H1a-H1d and participation intention as a dependent variable.*

3.1.1. Interest on nuclear energy and decommissioning

According to the VBN theory, after problem awareness or risk perception, there are two more aspects that influence interest and participation intention, namely, outcome efficacy and personal norm. However, van der Werff & Steg, 2016 argue that a more parsimonious model is needed which uses less steps and more general predictors of participation intention. Furthermore, these authors argue that interest and participation intention should be treated separately, because interest measures someone's interest on the topic and their willingness to receive more information (Sheppard et al., 1988; van der Werff & Steg, 2016), whereas participation intention measures their willingness to voluntarily commit to a project, discussion, or a decision-making procedure (Arnstein, 1969; Krütli et al., 2010; van der Werff & Steg, 2016). While interest can influence participation intention, it itself can be influenced by other predictors too (Brandmo & Bråten, 2018; Latré et al., 2019; Lavezzolo & Ramiro, 2018; Neblo et al., 2010; Perko et al., 2013; Pölzl-Viol et al., 2018; Webb, 2013). That is why, similar to risk perception, in this study we treat interest as a mediating variable, rather than an integrated aspect of participation intention.

Several studies on participation intention found that interest or curiosity about a certain topic influences an individual's participation intention (Hibbing & Theiss-Morse, 2002; Neblo et al., 2010; Spielberger & Starr, 1994; Tommasetti et al., 2018; Webb, 2013). While trying to answer the question of why some individuals are interested in topics that others might find dull and vice versa, Fink, 1994 argues that the main explanation is not interest in some matter or content. Engagement with an object or a matter in which a person is greatly interested proceeds in a much more productive and qualitative character than does engagement with an object in which a person has little or no interest (Fink, 1994; Tommasetti et al., 2018). Based on these arguments we hypothesize that:

[H3]: More interest in nuclear energy and decommissioning leads to higher participation intention in decision-making regarding decommissioning of NPPs.

Similar to risk perception, interest in nuclear energy and decommissioning can also be influenced by trust, attitude towards nuclear energy, living in the vicinity of a nuclear installation, and ideological position. For instance, political, risk and nuclear-related studies have found that people that have higher interest about a certain matter at hand are those who have low trust in authorities (Brandmo & Bråten, 2018; Neblo et al., 2010; Perko et al., 2013; Webb, 2013) and are more dissatisfied or against that matter (Latré et al., 2019; Neblo et al., 2010; Webb, 2013). Furthermore, it has been argued that in post-nuclear accident issues, local actors in communities with personal experiences linked to nuclear (e.g. living in the vicinity of a nuclear installation) are more interested in the nuclear-related activities (Pölzl-Viol et al., 2018). This is also because people living close to a nuclear installation are much more often addressed in communication and decision-making practices (e.g. emergency exercises, consultations, etc.) (Perko et al., 2013; Perko, Tafili, et al., 2019). By combining the VBN theory with the above-mentioned arguments we hypothesize that:

[H4a] Individuals that have lower trust in nuclear industry's capacity to decommission are more interested in the topic of nuclear energy and decommissioning.

[H4b] Individuals that have more negative attitudes towards nuclear energy are more interested in the topic of nuclear energy and decommissioning.

[H4c] Individuals living close to nuclear installation are more interested in the topic of nuclear energy and decommissioning.

[H4d] Individuals that are more ideologically leftist (biospheric values & altruistic values) are more interested in the topic of nuclear energy and decommissioning.

[H5] *Interest in nuclear energy and decommissioning will serve as a mediator between the explanatory variables as expected by hypotheses H4a-H4d and participation intention as a dependent variable.*

Levels of citizen participation based on Arnstein's ladder: the dependent variable

Public participation can have different levels of engagement. The VBN theory focuses on different forms of participation. Such forms can be activism (active involvement in organizations and demonstrations), non-activist behavior in the public sphere (approval of regulations or willingness to pay more for a certain cause), private-sphere activism (e.g. buying environmental-friendly goods), and behaviour in organizations (Stern, 2000; Stern et al., 1999). For the general purpose of this paper, however, we are more interested in the *extent* to which an individual wants to participate in decision-making related to decommissioning, rather than other forms of behavioral engagements. The extent of public participation in decision-making can have different levels of intensity. Arnstein (1969) developed for this purpose a "ladder of citizen participation" which consists of an escalating series of engagement including manipulation, therapy, informing, consultation, placation, partnership, delegation and citizen control. The influence of citizens on decisions is lowest in the first two rungs of the ladder (labelled as 'non-participation') where the main goal of decision-makers is to "educate" and "cure" citizens. Rungs 3, 4, and 5 are labelled as 'degrees of tokenism' and are levels in which citizens are in dialogue with public authorities but they have no influence on their decision. The last three rungs of the ladder are labelled as 'citizen power' and these are the levels in which citizens have appointed seats in decision-making committees and/or deal themselves with the policy-making process and as such they influence decisions to a greatest level (Arnstein, 1969). Similar distinction was later made on other studies related to public participation (Almond & Verba, 2003; Krütli et al., 2010).

Given that in this study we want to know the extent to which an individual is willing to co-decide about certain issues or have a significant impact in the outcomes of a certain process (Arnstein, 1969), we divide participation intention in three levels, namely non-participation, tokenism and citizen power. This way, we can see the impact that risk perception and interest on nuclear energy and decommissioning have on all these three levels. In figure 2 we show the hypothesized model which includes Arnstein's ladder in the structure of a combination of VBN and other theories in order to provide a better fit for the special context of decommissioning.

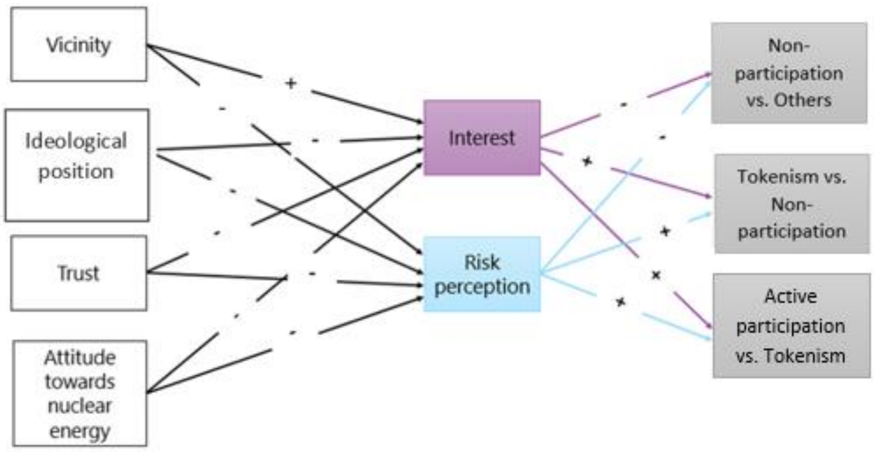

Figure 2. Hypothesized model explaining participation intention resulting from the combination of different theories and Arnstein's ladder of participation.

Method

Data Collection

Participation intention regarding decommissioning of nuclear power plants was analyzed in a large public opinion survey related to perceptions and attitudes towards nuclear technologies in Belgium in 2015 (Turcanu et al., 2015). The survey data were collected using Computer Assisted Personal Interviews (CAPI), which entailed face-to-face interviews at the respondents' homes, the answers being directly recoded and stored on a portable hard disk. The sample consisted of N=1028 Belgian adults (18+) and is representative for the Belgian population with respect to gender, age, region and education (Table 1). Most items in the survey were formulated as questions or statements, while answering categories were mostly expressed with a five points Likert-scale. The answering categories typically ranged from 'strongly disagree' to 'strongly agree', but some of them were adjusted to the context of the statement or question.

[Table 1 about here]

Variable measurement

Dependent variable: Participation intention

In order to find out to what extent the respondents would like to participate in decision-making related to decommissioning, our survey first introduces the context regarding decommissioning the following way: "*The Belgian nuclear power plants are reaching the end of their operating life and will be shut down permanently in the near future. These facilities will need to be decommissioned. This process is the removal of radioactivity from the installation to the point where control is no longer necessary*". Afterwards, it asks the participants to what extent they would like to participate in the decision-making concerning the decommissioning of nuclear power plants[7]. The answering categories derive from Arnstein's ladder (Arnstein, 1969) and range from: 1- I don't want to participate; 2- I want to receive information about the plant to be decommissioned; 3- I want to receive information and express my opinion; 4- I want to participate in a dialogue towards a decision; and 5- I want to be an active partner in decision-making. Respondents could only choose one option. In order to better fit our hypothesized model and the

[7] Note that this variable measures public participation intention once a decision to decommission nuclear installations has been made. We have also considered the extent to which the hypothesized explanatory variables would be related to public's preferences on what should happen with a nuclear installation once it is shut down, however, given that there was no significant correlation, we have not included it in the main analysis.

empirical analysis, we group these answering options in three separate dependent variables. The first one is called “non-participation” and it measures the first category (I don’t want to participate) versus the other four. The second dependent variable is called ‘tokenism’ and it consists of category 2&3 versus category 1. The last dependent variable is called ‘citizen power’ and it consists of category 4&5 versus category 2&3.

Independent variables:

Trust in nuclear industry’s capacity to decommission is conceptualized as the extent to which citizens trust the financial, technological and expert capacity of the nuclear industry and Belgian authorities to successfully decommission a nuclear power plant.

This variable is measured with four items (see table 2), namely, 1. The nuclear industry has the technology required to successfully decommission nuclear power plants; 2. The nuclear industry does not have the expertise required to successfully decommission nuclear power plants; 3. The owner of the nuclear plants has the financial resources needed for decommissioning; and 4. I trust the Belgian authorities to control what the nuclear industry does in the field of decommissioning. The participants had to choose answers on a scale from 1. Strongly Disagree to 5. Strongly Agree. PCA (Principal Component Analysis) with these four items resulted in one factor which explains 47% of variance and has a Kaiser-Meyer-Olkin (KMO) index of 0.625. The reliability scale resulted with α =0.615.

[Table 2 about here]

Similar to (Latré et al., 2018; Perko, Turcanu, et al., 2012; Turcanu et al., 2014) *attitude towards nuclear energy* is measured with three items. These asked the respondents whether 1) they believed that ‘the benefits of nuclear energy outweigh the disadvantages’, 2) that ‘reducing the number of NPPs in Belgium is a good cause’, and 3) that ‘NPPs endanger the future of our children’. The answering categories ranged from 1= ‘strongly disagree’ to 5= ‘strongly agree’. For the purpose of the analysis, the items have been reverse-coded where a lower score means a more negative attitude whereas a higher score means a more positive attitude. PCA with these three items resulted in a single factor, explaining 66% of the variance. All of the three items have factor loadings of higher than 0.7 with a KMO index is 0.665 and a reliability scale of α =0.743.

[Table 3 about here]

To measure the *ideological position of the participants* in our study, we asked them which political party would they vote for in case a federal election were organized next Sunday. The respondents selected their favorite party and these answers were re-coded in a categorical variable were 1 means left, 2- center, and 3- right.

To see whether the participant ever lived *in the vicinity of a nuclear facility* we asked the respondents whether they have ever lived in an area close (within a 20 km radius) to a nuclear installation (power plant or nuclear research institute). They could answer with 1= yes or 2= no.

Mediating variables:

In order to measure people's *interest in nuclear energy and decommissioning* we use three items. The first item asks the respondents the following question: "In the past year, how often have you discussed about nuclear energy with other people?" (Answers ranging from 1= never to 5= very often). The second item asks the respondents if they would take the time to read an article about nuclear energy if they encountered it (answers ranging from 1= definitely not to 5= definitely yes). Finally, the third item asks whether the respondents ever thought of what happens after a nuclear power plant is shut down? They could answer with 1= Yes or 2= No, which were later reverted in order to fit the analysis better.

PCA with these three items resulted in a single factor, explaining 57% of the variance. All of the three items have factor loadings of higher than 0.7 with a KMO index is 0.627 and an α = 0.621.

[Table 4 about here]

Risk perception in this study is defined as a subjective judgement or belief regarding characteristics and severity of potential risks (Renn, 2008b). Similar to Latré, Thijssen, & Perko (2019), we measure risk perception with three items. Respondents were asked how they perceive the potential personal health risk within the next 20 years from: radioactive waste, an accident in a nuclear installation, and a terrorist attack with a radioactive source. Answers ranged from 'no risk at all' (1) to 'a very high risk' (5).

The PCA of these variables resulted in a single factor which explains 70% of the variance. As table 5 shows, all factor loadings are higher than 0.65 and the KMO index is 0.691. The reliability of this scale is α =0.792.

[Table 5 about here]

Results

Descriptive analyses

Descriptive results show that participation intention is quite low with almost half of the respondents (44%) not wanting to participate at all and around 27% only wanting to receive information, without becoming actively involved. 19% of the respondents want to receive information and express their opinion whereas only about 8% of the respondents want to actively participate in decision-making regarding decommissioning. As can be seen in table 6, trust in nuclear industry's capacity to decommission seems to be fairly high with a mean of 3.22 which is higher than the middle point. The same applies to attitude towards nuclear energy, which is higher than the median, pointing to a modest positive attitude towards nuclear energy. The respondents' ideological position ranges from about 41% considered as leftists, 15% favouring the centrist parties and around 43% favouring the right ones. Regarding the citizens' interest in nuclear energy, the majority of the participants (59%) stated that they would take the time to read a newspaper article about nuclear energy. However, most of them (71%) stated that they have never or very rarely discussed about nuclear energy with other people and that they have never thought about what happens when a nuclear power plant is shut down (62%). This shows a rather low interest from the citizens although most of the reactors in Belgium are already approaching the end of their operation time. Risk perception seems to be quite high as well, with a mean of 4.19.

[Table 6 about here]

Who is willing to participate?

The hypothesized model of this paper included mediation variables and indirect relationships, therefore, we conducted a mediation analysis in Structural Equation Modelling (SEM) in order to test it. SEM is a multivariate technique that allows for examination of a series of interrelated causal relationships by combining aspects of factor analysis and multiple regression. This way, we can see which variables influence interest and risk perception, and then the effect that the latter have on participation intention.

We applied a Confirmatory Factor Analysis (CFA) to test and evaluate the results of our hypotheses. We conducted three separate analyses for the three different dependent variables and then integrated them in the path model (see figure 3) for simplicity reasons. All three models resulted with good fits. In CFA and SEM, the chi-square test is easily affected by the sample size. Therefore, here we report the comparative fit index (CFI), the standardized root mean square residual (SRMR), and the root mean square error of approximation (RMSEA) as criteria for the goodness of fit. A good model fit is found when the SRMR is equal to or lower than 0.08, the RMSEA is equal to or lower than 0.08, and the CFI is equal to or over 0.95 (Hair et al., 2010). The model we applied is visually explained in figure 3 below where only the significant effects are shown.

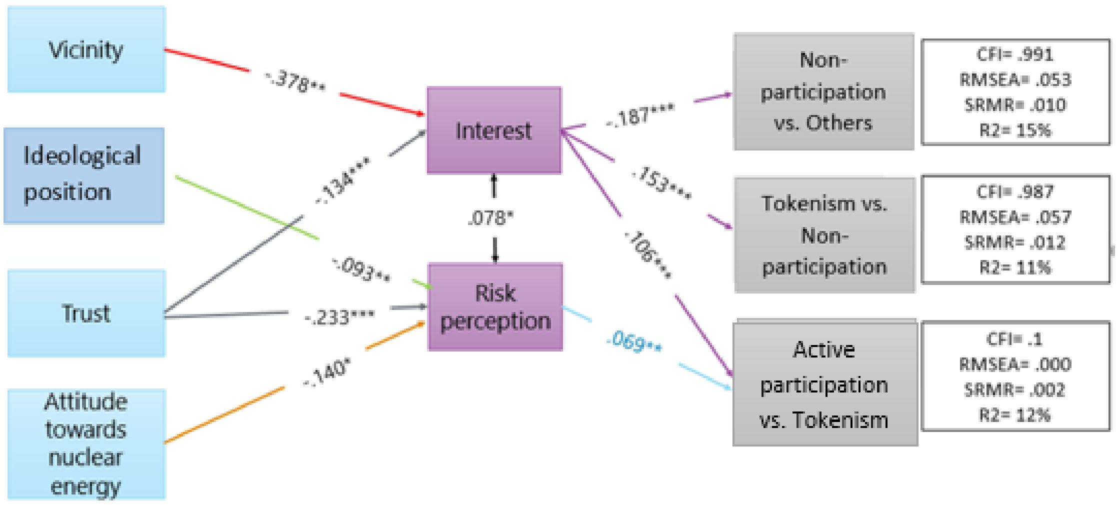

Figure 3: The final model based on SEM, including model statistics and significant standardized pathways.
$*p < 0.05$; $**p < 0.01$.; $***p < 0.001$.

The model with Non-participation as a dependent variable has a CFI of 0.991, a RMSEA of 0.053 and a SRMR of 0.01 which indicate a good fit of the model. The R-square of this model is 0.153 which means that the model predicts 15% of the variance in Non-participation variable.

The second model in which Tokenism is the dependent variable has a CFI of 0.987, a RMSEA of 0.057 and a SRMR of 0.012. The model predicts 11% of the variance in Tokenism, which is a comparison of people that don't want to participate at all versus people that want to 'hear and be heard'.

In the last model the dependent variable is called Citizen power and it is a comparison of people that want to receive information only or people that want to receive information and express their opinion versus people that want to participate in more active forms such as taking part in dialogues or being active partners in decision-making. This model has a CFI of 0.1, a RMSEA of 0 and a SRMR of 0.002. The model predicts 12% of the variance of this dependent variable.

As can be seen in figure 3, risk perception is influenced by ideological position, trust and attitude towards nuclear energy. This means that people who are more ideologically leftist (stronger biospheric and altruistic feelings), have lower trust in nuclear industry's capacity to decommission an NPP, and have more negative attitudes towards nuclear energy perceive higher radiological risks. This was expected from our hypotheses 1a, 1b and 1d which resulted from the modified model of the VBN theory. Hypothesis 1c, however, cannot be confirmed as vicinity does not have a significant impact on risk perception in this model. Furthermore, one can see that risk perception serves as a mediator between the independent variables and participation intention which also supports our hypothesis 2a.

In our hypothesized model we also suggested that vicinity, ideological position, trust and attitude towards nuclear energy will also influence interest in nuclear energy and decommissioning. This, however, holds true only for vicinity and trust as these are the only independent variables that influence interest. Given that people who have ever lived close to a nuclear installation and who have lower trust in nuclear industry's capacity to decommission are more interest in nuclear energy and decommissioning, we confirm hypotheses 4a and 4c, whereas we reject hypotheses 4b and 4d given that ideological position and attitude towards nuclear energy have no significant impact on interest. Hypothesis 5 can also be confirmed given that as the results show, interest in decommissioning of nuclear installations serves as a mediator between vicinity, trust and participation intention.

Finally, we hypothesized that risk perception (H2) and interest (H3) will influence participation intention. After separating participation intention into three separate dependent variables, the results of the model show that interest has a significant impact on all of these three dependent variables whereas risk perception only influences citizen power which is the variable related to more active participation. Based on these results we can see that interest negatively influences non-participation which means that people who are more interested on the topic of nuclear energy and decommissioning are less likely to stay passive. As expected, the opposite applies to tokenism and citizen power which means that people who are more interested, are more likely to either want to 'hear and be heard' or to have active participation such as being active partners in decision-making processes. Although risk perception has a significant impact on citizen power only, this means that people who have higher radiological risk perception are more likely to be willing to be actively involved instead of willing to receive information only. Based on these results, we can confirm both, hypothesis 2 as well as hypothesis 3 related to the impact of interest and risk perception on participation intention.

A summary of the direct, indirect and total effects of all the variables on the dependent ones is provided in table 8, appendix A.

Discussion

Based on a public opinion survey in Belgium, this study investigated citizen participation intention regarding decommissioning of nuclear power plants. Theoretically, the paper is built on the Value-Belief-Norm theory which included Arnstein's ladder of participation as a scaled indicator for measuring intention to act as a means to better fit the topic of nuclear decommissioning. We hypothesized that participation intention is affected by interest and risk perception directly, and by vicinity, trust, ideological position and attitude towards nuclear energy indirectly, through interest and risk perception.

Not surprisingly, the findings of the study pointed out that participation intention is influenced by risk perception and interest. People who are more interested on the topic of nuclear energy and decommissioning, and those who have higher radiological risk perception are more likely to be willing to actively participate in decision-making processes related to decommissioning of nuclear power plants. This was expected based on the different theoretical findings of the literature. For instance, the VBN theory argues that when individuals recognize that a certain circumstance, or technology poses threat to other people, other species or nature (problem awareness) they are more likely to act against it. This argument is in line with the result we obtained regarding risk perception. The impact of interest on participation intention, on the other hand, has a long history starting from the XIX century by James, (1891) who developed a theory focusing on the capacity of curiosity to affect human behaviour (Tommasetti et al., 2018). Later on, many other studies found that interest is the main driving behaviour behind participation intention and qualitative engagement (Hibbing & Theiss-Morse, 2002; Neblo et al., 2010; Spielberger & Starr, 1994; Tommasetti et al., 2018; Webb, 2013). While this makes sense also from a rational reasoning point of view, very little research has considered interest as a mediating variable, along with risk perception in order to see which predictors have an influence on these two mediators.

After doing so, in this paper we found the effect of trust, vicinity, altruistic and biospheric values, as well as attitudes towards nuclear energy on participation intention was fully mediated by risk perception and interest as mediating variables. Specifically, we found that risk perception is influenced by ideological position, trust and attitude towards nuclear energy, which means that people who are more ideologically leftist, are more negative towards nuclear energy and those that have lower trust on nuclear industry's capacity to decommission have higher radiological risk perception. This was mainly expected from the VBN theory as well as other theoretical findings, which suggested that risk perception is affected by values, attitudes, psychometric factors as well as ideological positions (Latré et al., 2019; Perko, Železnik, et al., 2012; Turcanu et al., 2014; Wiegman & Gutteling, 1995). These findings thus confirm earlier studies related to these relationships as well as the hypotheses that were created based on these arguments. However, while some variables (e.g. attitude towards nuclear energy) had significant direct effects in previous studies (Turcanu et al., 2014), in our study the effect was fully mediated by risk perception.

The hypothesis [H1c] that radiological risk perception will be influenced by the situation of whether someone has ever lived close to a nuclear installation or not could not be confirmed based on this study. Although this was expected mainly by the familiarity effect, which argues that people who are familiar and have experiences with the risk or hazard perceive lower risks (Renn, 2008b), the effect was not significant in our study. Vicinity influenced participation intention indirectly, however, through interest. As can be seen in table 8 (appendix A), people living closer to a nuclear installation are more likely to have higher participation intention.

Finally, the findings of the study suggest that people who have ever lived close to a nuclear installation, and those who have lower trust in nuclear industry's capacity to decommission an NPP are more interested on the topic of nuclear energy and decommissioning. This was expected from several studies who found that people who have low trust in authorities (Brandmo & Bråten, 2018; Neblo et al., 2010; Perko et al., 2013; Webb, 2013) as well as personal experiences with the risk or hazard (e.g. living in the vicinity of a nuclear installation) (Pölzl-Viol et al., 2018; Renn, 2008b) have higher interest about a certain matter at hand. Usually, people living close to a nuclear installation are much more often addressed in communication and included in decision-making practices (e.g. emergency exercises, consultations, etc.) (Perko et al., 2013; Perko, Tafili, et al., 2019), and this can serve as a boost to their interest and curiosity on similar nuclear-related activities.

In sum, based on the findings of this paper, it seems like the people that are more willing to participate in decision-making related to decommissioning are those that are more interested on the topic and have higher radiological risk perception (direct effects). Furthermore, people who are have lower trust, are ideologically leftists, have more negative attitudes towards nuclear energy and live in the vicinity of a nuclear installation are more likely to show a higher participation intention, albeit indirectly via interest and risk perception.

Will we be preaching to the converted? Recommendations for decision-making practices and future research

These findings give the impression of a "preaching to the converted" situation regarding participation intention. For instance, if we include only people that have already rather negative opinions and who are easily recruited, this would result in a negative bias in terms of fair representation of all viewpoints in the end of the joint decision-making process. As

Strandberg, Himmelroos, & Grönlund (2017:3) argue, “pre-existing [negative] views are likely to be bolstered in like-minded groups because individuals tend to value arguments supporting their own previously held position”. This way, if people with more negative views (e.g. lower trust, anti-nuclear, higher risk perception, etc.) are more likely to be actively involved, this could lead the discussion to end up with extreme, or at least very narrow, views (Sunstein, 2005). And because people usually seek social acceptance and tend to adjust their behaviour according to what they perceive as the dominant position in the group, opinion polarization or extremity bias can occur (Sunstein, 2007).

In order to prevent preaching to the converted, we need to find ways to include more diverse opinions in decision-making processes, for instance, by using stakeholder analysis to make sure that under-represented groups are also a part of the process as well as active conflict management to make sure that opinions and visions are properly interpreted and translated into results (Irvin & Stansbury, 2004). Furthermore, in the recruitment process the organizers of public engagement events should pay attention to potential biases and focus more on increasing the willingness to participate of those individuals who would normally not be willing to do so. To address this, participatory discourses are often used to make sure that ambiguities and value differences are addressed and common solutions are found (G. Rowe & Frewer, 2005). One suitable instrument to achieve this are randomly selected citizen panels or juries, which make sure to have a representative sample of the affected population. Although true representation of public may never be achieved, at least such citizen juries will ensure that there is high heterogeneity and mutual learning (Renn, 2008b). Furthermore, to make the event more attractive, the organizers should explain the advantages of participation and the consequences of not doing so; the advantages of achieving a common satisfactory result and the potential consequences of not doing so; they should clarify and guarantee in advance that participants will have a strong say in influencing the final decisions; and finally they should also organize such events at convenient time and venues (Perko, Monken-Fernandes, et al., 2019).

While this study adds to the scarce literature on decommissioning of NPPs by analyzing the predictors behind participation intention in the field of nuclear decommissioning, there are also some limitations which need to be better addressed in future research. For instance, we have faced the problem of 'inclined abstainers' in this study. This means that although we intended to measure participation intention, we cannot make any inference whether the respondents will actually participate in decision-making in reality. There are many cases where people intend to participate, but then fail to do so when they are faced with the opportunity to do so (Orbell & Sheeran, 1998). Furthermore, one criticism about this paper could be that we measured ideological position with one item only, namely by party preferences. However, given that parties in Belgium have clear and distinct position regarding nuclear energy, this item proves sufficient to measure the ideological stance of a respondent on this issue. Lastly, we are aware that the explained variance of the dependent variables is rather low, however, we believe that these results will serve as a good starting point for future research on participation intention related to nuclear decommissioning.

Based on these limitations we recommend further research to analyze whether making people aware that only those that already hold certain beliefs (e.g. less trustworthy, more interested, anti-nuclear) are willing to participate and that this could lead to biased results, might change their minds and make them more willing to participate. Furthermore, future research should also investigate the extent to which these explanatory variables apply to decision-making processes related to all environmental processes in general, and not only concerning decommissioning of nuclear installations, once a decision about it has been made. Different participatory techniques can also influence publics' willingness to participate in decision-making processes (Renn, 2008b). Hence, we recommend future research to explore more into this topic. Adding the outcome efficacy or public's perception on their ability to reduce perceived threats to the explanatory model would be an interesting investigation in future studies. Related to this, it would also be interesting to try to see whether telling people that even scientists and experts themselves are uncertain about some aspects of decommissioning, would increase public participation intention.

Conclusions and policy implications

Based on a public opinion survey in Belgium, this study analysed the extent to which individuals from the public intend to participate in decision-making regarding decommissioning of nuclear power plants and the factors that influence this intention. Relying on various experiences with public consultation and public engagement processes, as well as building on different empirical findings (European Commission, 2010, 2013; Turcanu et al., 2014), we started with the assumption that except for anti-nuclear protests or activism, a major part of the public in general does not intend to actively participate in organized decision-making procedures. This was confirmed by the results of the descriptive analysis which revealed that only 8% of the respondents would like to be actively engaged in decision-making processes concerning decommissioning of NPPs. Decommissioning of nuclear power plants is a vivid example of the link between a technical task and the society. Citizen involvement in decision-making about different topics is recommended and required by multiple EU science policy strategies and governance frameworks and this has an instrumental, normative and a substantive rationale.

Drawing on a theoretical frameworks such aselements of the Value-Belief-Norm theory, psychometric paradigm, deliberative democracy and augmented by degrees of involvement as defined by Arnstein's ladder (Arnstein, 1969), we found that the people that are more willing to participate in decision-making related to decommissioning are those who are more interested on the topic, have higher radiological risk perception (direct effects) are less trustworthy, are ideologically leftists, have more negative attitudes towards nuclear energy and live in the vicinity of a nuclear installation. This shows that while public participation in decision-making seems as a promising way for inclusive, transparent and mutual decision-making, there are still some challenges that need to be addressed in practice. For instance, based on our results people that are already interested on the topic and hold certain negative opinions related to nuclear energy are more willing to participate than those who are more in favor of nuclear energy. Although these people may raise legitimate points and bring good arguments in the discussion, we need to make sure that all diverse opinions are represented in order for the discussion to be fair and comprehensive (Sunstein, 2007).

To prevent this situation, and to stop preaching to the converted, we recommend that, although challenging, the organizers of public engagement events pay attention to potential biases in public participation and invest resources into motivating individuals that would normally not participate to take part in the decision-making process. Although inclusion and exclusion often refer to the ethnic, racial, gender diversity of the people taking part in public participation, based on the results of this study we argue that other factors such as interest, risk perception, trust, attitudes and ideological position should also be considered when including people in decision-making regarding decommissioning of NPPs.

Research data

Data used and analyzed for this article are available here:
https://data.mendeley.com/submissions/ees/edit/d9sdcz9mpn?submission_id=JEPO_27354&token=7ece12ab-8724-4f56-921c-6b06ef36ed8a

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Appendix 1

Table 1: Socio-demographic characteristics of the sample.

Variable	**Belgian population (%)**	**Survey sample (N=1028) % (N) – weighted sample in %**
Gender		
Men	48.6	49.9
Women	51.4	50.1

Age		
18-34	26.84	20.7
35-54	34.99	38.2
55+	38.16	41.1
Education		
Lower (primary and lower secondary)	28.7	25.7
Intermediate (higher secondary)	40.3	41.7
Higher	31.3	32.6
Region		
Flanders	58.9	58.9
Wallonia	31.8	33.0
Brussels	10.2	8.2

Table 2: PCA results regarding trust as a factor.

Items	Factor loadings
- The nuclear industry **has the technology** required to successfully decommission nuclear power plants.	.841
- The nuclear industry does not have **the expertise** required to successfully decommission nuclear power plants (reverted).	.715
- The owner of the nuclear plants has the **financial resources** needed for the decommissioning.	.647
- I trust the Belgian authorities to **control** what the nuclear industry does in the field of decommissioning.	.511

Table 3: PCA results regarding attitude towards nuclear energy as a factor.

Items	Factor loadings
- Overall, the benefits of nuclear energy outweigh the disadvantages	.748
- The reduction of the number of nuclear power plants in Belgium is a good cause	.841
- Nuclear power plants endanger the future of our children	.846

Table 4: PCA results regarding interest as a factor.

Items	Factor loadings
- In the past year, how often have you discussed about nuclear energy with other people?	.803
- If you saw an article about nuclear energy, would you take the time to read it?	.733
- Have you ever thought about what happens with a nuclear power plant after it is shut down?	.720

Table 5: PCA results regarding risk perception as a factor.

Items	Factor loadings
- How do you perceive the potential risk to your health within the next 20 years from radioactive waste?	.765
- How do you perceive the potential risk to your health within the next 20 years from an accident in a nuclear installation?	.707
- How do you perceive the potential risk to your health within the next 20 years from a terrorist attack with a radioactive source?	.650

Table 6: Descriptive results

	NP[a]	Tokenism	Citizen power	Risk perception	Interest	Vicinity	Biospheric and altruistic values (ideological position)[b]	Attitude towards Nuclear Energy
Mean	1.45	1.50	1.14	4.19	2.24	1.76	2.01	2.81
SD	.498	.500	.357	1.348	1.149	.426	.920	1.16

[a] NP= Non-participation
[b] Left/right ideological position.
**p < 0.05; **p < 0.01.*

Table 7. Correlation table

a	1	2	3	4	5	6	7	8	9
1. Non-Participation	1								
2. Tokenism	-1.000**	1							
3. Citizen power	.[b]	.[b]	1						
4. Risk perception	-.093**	.070*	.112**	1					
5. Interest in nuclear energy	-.389**	.354**	.240**	.061	1				
6. Vicinity	.139**	-.136**	-.018	-.033	-.138**	1			
7. Biospheric and altruistic values (ideological position)	.085*	-.066	-.088	-.135**	-.112**	.037	1		

8. Trust in nuclear industry's capacity to decommission	.018	.005	-.102*	-.293**	-.097**	.033	.008	1	
9. Attitude towards Nuclear Energy	.062	-.037	-.119**	-.334**	-.139**	.091**	.274**	.211**	1
Mean	1.45	1.50	1.14	4.19	2.24	1.76	2.01	3.22	2.81
SD	.498	.500	.357	1.348	1.149	.426	.920	1.122	1.16

[a] Range of measures: Non-participation = 1 (willing to participate in any form), 2 (not willing to participate at all); Tokenism= 1 (not willing to participate at all), 2 (willing to receive info only); Citizen power= 1 (willing to receive info only), 2 (willing to actively participate); Risk perception= higher score means higher risk perception; Interest in nuclear energy= higher score means higher interest; Vicinity= 1 (lives close), 2 (doesn't live close); ideological position 1 (left), 2 (center), 3 (right); Trust = higher score means higher trust; Attitude towards nuclear energy= lower score means more negative attitude.
[b] Could not be computed.

**p* < 0.05; ***p* < 0.01.;*

Appendix 2

Table 8. Direct, Indirect, and Total Effects of the Model Variables on participation intention (divided in stealth democracy, tokenism and citizen power), based on SEM.

	Non-participation			Tokenism			Citizen power		
Variable	***Direct***	***Indirect***	***Total***	***Direct***	***Indirect***	***Total***	***Direct***	***Indirect***	***Total***
Vicinity	.033	**.07*****	**.103***	-.055	**-.064*****	**-.119****	.012	-.028	-.016
Biospheric and altruistic values (ideological position)	0	.010	.010	0	-.005	-.005	0	-.012	-.012
Trust	-.010	**.025***	.010	.011	-.012	-.002	.001	**-.030*****	-.030

Attitude towards nuclear energy	.003	.014	.017	-.018	-.007	-.025	-.009	**-.018****	-.027
Interest	**-.187*****	0	**-.187*****	**.153 *****	0	**153*****	**.106*****	0	**.106*****
Risk perception	-.001	0	-.001	-.034	0	-.034	**.069****	0	**.069****

**p < 0.05; **p < 0.01.; ***p < 0.001.*

Chapter 5: Uncertainty communication related to decommissioning of nuclear installations: Testing its impact on feelings, information seeking, and public participation intention

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Abstract

Decommissioning of nuclear installations are complex processes that involve many uncertainties, and need to be managed in a socially-responsible way. While a lot of research and practical guidelines exist on how to address technical and financial-related uncertainties in decommissioning, communication of such uncertainties, and the impact it has on information receivers has so far not been tested.

We address this gap by testing the impact that communication of different types of decommissioning-related uncertainties has on feelings, information-seeking behavior and public participation intention. We form the hypotheses based on the Cognitive Functional Model (Nabi, 1999), Uncertainty Reduction Theory (Babrow, 2001; Bradac, 2001) and Uncertainty Management Theory (Brashers, 2001), which are then tested via a survey-embedded experiment, with a representative sample of the Belgian population (N=1060).

Results show that communication of uncertainties neither influenced information-seeking behavior, nor participation intention. It led, however, to slightly more negative feelings such as worry and pessimism. Nevertheless, when asked if they would like to receive information about decommissioning that involves uncertainty, the majority of participants

(62%) said that they would like to receive such information. We conclude by arguing that uncertainty communication should still be a crucial part of scientific communication and the more people are encountered with it, the more comfortable they become with receiving uncertainty information and thus having less negative reactions towards it. Further recommendations for future research are provided in the conclusions section.

Keywords: Uncertainty communication; feelings; information seeking; public participation; decommissioning of nuclear installations

Introduction

The topic of nuclear energy has managed to keep its saliency over the years. Various events such as accidents in Three Miles Islands, Chernobyl, and Fukushima Daiichi Nuclear Power Plant (NPP); climate crisis; and uncertainties about energy security have influenced people's risk-and-benefit perceptions and attitudes towards nuclear energy, leading to pro, against, and in-between arguments about it (Abbott et al., 2006; Hoti, Perko, & Turcanu, 2021; Latré et al., 2018; Perko, 2016). A similar debate was present recently in the European Union (EU) level about the EU taxonomy Regulation (Regulation (EU) 2020/852) which after many back-and-forth discussions, decided to label nuclear energy as green and as contributing to climate neutrality (European Commission, 2022), thereby sparking many reactions among environmental organizations, political groups, scientists and experts, and member state (MS) representatives in the European institutions. Furthermore, in 2022, Russia invaded Ukraine, and amid international sanctions it received, it also decided to restrict fossil fuel export to the EU MS, causing uncertainties about energy security, rapid increase in energy prices in Europe, and an overall energy crisis. This is why many countries (e.g. Belgium, Germany, Japan) have decided to extend the lifetime of some of their nuclear reactors (Euractiv, 2022; Politico, 2022). Among all these geopolitical uncertainties, there is one thing that is certain about nuclear energy: Europe's nuclear reactor fleet is ageing, and many nuclear reactors are being taken out of operation after finishing their operational lifetime, and will soon have to be decommissioned (Hirose & McCauley, 2022; International Energy Agency (EIA), 2020; Latré et al., 2019).

Decommissioning of nuclear installations is a process that involves removing the used fuel from the nuclear reactor, dismantling the parts that contain radioactive products (e.g., the reactor vessel); as well as removing or dismantling contaminated materials from the facility (Hoti, Perko, Thijssen, et al., 2021). Projects of decommissioning of nuclear installations have to be managed in a socially-responsible way (Invernizzi et al., 2017), because this process is related to many societal concerns such as: decreasing employment rate, reduction of revenues for the host municipality, uncertainty about the future use of the affected land, outmigration of workforce and consequent impoverishment of local resources, depressed value of the property, loss of competences, time-frame of completing the decommissioning project, financial cost, remaining radioactivity, where to store the radioactive waste, etcetera (Martell & Perko, 2022).

But what does a socially-responsible way of managing a nuclear decommissioning project mean? Complex issues such as decommissioning projects that involve uncertainties, a variety of values, high stakes, and urgent decisions (Funtowicz & Ravetz, 1997) require science to contribute to decision-making by representing a variety of perspectives in policy problems (Petersen et al., 2011). According to the Post-Normal Science (PNS) paradigm, this variety of perspectives is reached through three key elements: 1) the management of uncertainty (paying attention not only to technical/methodological uncertainties, but also uncertainties that arise from epistemological, societal and ambiguous nature); 2) the management of the plurality of perspectives within and without science (emphasis on inter-and transdisciplinary efforts from various areas such as science, business, politics, and society); and 3) the extension of the peer community (including representatives from social, political, and economic domains to discuss different dimensions and implications of decisions, and in addition for reliability and validity, to also test for “social robustness”) (Petersen et al., 2011; Ravetz & Funtowicz, 2015). According to this approach, problem framing should go hand-in-hand with involvement of stakeholders, and reporting of uncertainty information (Petersen et al., 2011).

Different members of the public, especially the affected population, are one of the main stakeholders when it comes to projects of decommissioning nuclear installations (Perko et al., 2019). This is why several European regulations[8], the Aarhus Convention (United Nations, 1998, 2014), as well as multiple scholars (Hage & Leroy, 2008; Invernizzi et al., 2017, 2020; Krütli et al., 2010; Liu et al., 2020, 2021; Pellizzoni, 2003; Perlaviciute, 2022; Renn, 2015; Turcanu et al., 2014) recommend and/or require public participation in decision-making procedures related to decommissioning of nuclear installations. Apart from the fact that the public must be involved in decisions that they are affected by, public participation in decision-making procedures has multiple benefits. It allows for inclusion of more, and various perspectives, opens up for a wider range of (policy) options, assists in avoiding type III errors (addressing "wrong" problems), and reduces the likelihood of unforeseen impacts of policies/solutions chosen by extending the peer community from only scientific, towards political, social and economic domains (Hage & Leroy, 2008; Pellizzoni, 2003; Petersen et al., 2011; Wesselink et al., 2011).

However, based on existing research on public participation in decommissioning-related decision-making procedures, we know that so far, public participation intention is rather low, and it is mainly influenced by interest, knowledge, and familiarity with the topic (Hoti, 2022; Hoti, Perko, Thijssen, et al., 2021). Given that so far we know that people that do not feel knowledgeable enough with the decommissioning topic, are less likely to be willing to participate, and given that decommissioning projects are associated with many uncertainties, in this article we test whether telling people that even experts themselves

[8] For instance, the amended Environmental Assessment Directive (2014/52/EU) and European Council Directive (2011/92/EU).

are uncertain about some aspect of decommissioning influences their participation intention.

In order for the decision-making procedure to be transparent and there to be informed decisions, communication of uncertainties is crucial (Hoffman et al., 2011). The International Atomic Energy Agency (IAEA) has produced guidelines on how to address uncertainties in decommissioning costs, which are mainly focused on improving estimates (IAEA, 2017). However, testing the impact of uncertainty communicating on the receivers of the information is not included in these guidelines. In this article we thus test the impact of uncertainty communication on feelings, information seeking behavior, as well as public participation intention, by focusing on Belgium, as a case study. Belgium is a good focus point given that all of its nuclear reactors are approaching the end of their operational lifetime and will need to be decommissioned soon (Latré et al., 2019). Despite the fact that due to the current energy crisis, Belgium decided to extend the operational lifetime of its youngest two reactors, as part of its phase-out plan, in September 2022, the first Belgian nuclear power reactor was shut down and what follows now is decommissioning. The findings of this study will thus not only add to the missing literature on the impacts of uncertainty communication in decommissioning, but they will also provide practical recommendations for the upcoming decommissioning projects in Belgium and other democratic countries.

In the next section we explain the hypotheses of this study and the theoretical background behind them. Afterwards we explain the method used and the results, which are then followed by a discussion. Finally a conclusion of the study including practical recommendations as well as recommendations for future research is provided.

Theoretical argument

The linkage between uncertainty communication, feelings and public participation intention is a complicated one. This is mainly because of the contradictory findings on the impact that uncertainty communication has on feelings. Some studies found that uncertainty communication causes negative feelings (e.g. fear and anger) (Han et al., 2010; Knoblauch et al., 2018), whereas others found that communication of uncertainties actually reduces negative feelings (e.g. worry, fear, proneness to backlash) (Jensen et al., 2016; Jensen, 2008; Maxim et al., 2013). While there is existing research focusing either on the relationship between uncertainty communication and feelings (Brashers, 2001; Jensen, 2008; Jensen et al., 2011; Visschers, 2018), or between feelings and public participation (Marcus et al., 2002, 2011; Nabi, 2002), the causal chain among these three factors has not yet been empirically tested when it comes to uncertainty communication. However, there are some expectations we can draw from existing research. In this article, we build the theoretical argument on a combination of three theories, namely, the Cognitive Functional Model (Nabi, 1999), Uncertainty Reduction Theory (Babrow, 2001; Bradac, 2001) and Uncertainty Management Theory (Brashers, 2001).

The Cognitive Functional Model (CFM) (Nabi, 1999) argues that discrete negative feelings that are induced from a specific message (e.g. uncertainty information) influence information processing and subsequent attitude change. Participants that receive uncertain information, are more likely to seek reassurance, and given that further information may offer it, they must seek more information or engage in decision-making procedures to find out if such reassurances will be met (Nabi, 1999). In such cases, people that believe that taking action will lead to less uncertainty will be more likely to participate (Van ’t Klooster & Veenman, 2021). Similar arguments are raised also by the Uncertainty Reduction Theory (URT) (Bradac, 2001) which poses that people are constantly trying to reduce uncertainty by seeking more information. Furthermore, one study about COVID-19 found that contradictory information caused increased levels of distress, particularly for people who have a high intolerance of uncertainty. More specifically, people that had lower uncertainty intolerance and that received contradictory information, were more likely to seek information (by searching online), and showed higher levels of fear and social-distancing behavior (Baerg & Bruchmann, 2022).. Based on this, we hypothesize that:

H1: Participants that receive uncertainty communication are more likely to a) seek information and consequently to b) be willing to participate in decision-making procedures related to nuclear decommissioning than those in the control group.

H2: Participants that prefer to receive information about decommissioning even if some aspects are uncertain, are more likely to a) seek information and b) be willing to participate in decision-making procedures concerning decommissioning.

Contrary to URT, though, the CFM argues that based on the type and intensity of feeling that uncertainty communication generates, the receiver of the information will have either an avoidance-based or an approach-based response (Nabi, 1999). Similarly, Uncertainty Management Theory (UMT) (Brashers, 2001) argues that the impact of uncertainty communication on participation intention is mediated by the type of feeling generated. People see uncertainty either as a threat (when perceived as endangering health or safety (Brashers et al., 2006)) or as an opportunity (e.g. presence of scientific uncertainty has been found to cause less concern about climate crisis among people (Visschers, 2018)). Negative feelings are linked to higher willingness to seek information about a situation, but also to participate themselves in such a situation. This is because negative feelings point to an undesirable situation that needs to be addressed. More specifically, feelings motivate people to change the relationship with the environment for two reasons: 1) to resolve the problematic situation which will then in turn preferably 2) alleviate those negative feelings (Nabi, 2002). While previous research (Marcus et al., 2002) has divided between approach-based (e.g. anger) and avoidance-based (e.g. fear) feelings, and found that these separate feelings lead to separate reactions to information (e.g. anger causes people to participate more, whereas fear makes individuals shrink from action (Karl, 2021)), when such information is accompanied with uncertainty, research shows that the emotional reaction is the same (Nabi, 2002). More specifically, when a message is accompanied with uncertainty, should there be a negative emotion or feeling generated, it will lead to higher information seeking behavior and motivation to engage with the message's source (Nabi, 1999, 2002). In comparison to previous research, in this article we do not focus on strong emotions such as anger or fear, given that decommissioning of nuclear installations in Belgium is a topic that people are not very much concerned with (Hoti, Perko, Thijssen, et al., 2021). For this reason, we focus on feelings that fit better in this case, namely worry versus tranquility, and pessimism versus optimism, which are described in more depth in the operationalization section. Based on these arguments, we hypothesize that:

H3: The impact of uncertainty communication on a) information seeking behavior and consequently b) public participation intention related to nuclear decommissioning is mediated by the type of feeling (positive vs. negative) generated from uncertainty communication.

Apart from uncertainty communication, research has continuously shown that there are other important factors predicting information seeking behavior and public participation intention. Attitude towards participation is one of them. Studies over the years have found attitude towards participation as one of the main predictors concerning this variable (Ajzen, 1985; Henningsson et al., 2015; Hoti, Perko, Thijssen, et al., 2021; Turcanu et al., 2014). Similarly, based on the CFM, individuals who believe that the information received through participation will provide reassurance against the negative feeling, will be more likely to participate (Nabi, 2002). Thus, we hypothesize that:

H4: Participants with a more positive attitude towards participation (i.e. believing that their participation is worthwhile, rewarding, and interesting) will be more likely to a) seek information and b) participate in decision-making procedures.

There is an extensive amount of research on the inter-linkage between risk perception, feelings and public participation too. On the one hand, we have research on “risk as feelings” which refers to individuals’ instinctive reactions to danger and threat (Slovic et al., 2004; Slovic & Peters, 2006: 322). On the other hand, there is research arguing that emotions or feelings influence risk perception itself, with fear amplifying risk estimates, versus anger attenuating them (Lerner et al., 2003; Slovic & Peters, 2006). Finally, it has been found that the other way around is also possible, with risk perception influencing feelings (Contzen et al., 2021; Nabi, 1999; Oh et al., 2021; Vrieling et al., 2021), and consequently also information seeking behavior (Grasso & Bell, 2015; Huurne & Gutteling, 2008; Nabi, 2002; van Valkengoed et al., 2022) and public participation intention too (Hoti, Perko, Thijssen, et al., 2021; Marcus et al., 2002; Neblo et al., 2010; Turcanu et al., 2014). The CFM argues that in order to experience negative feelings, the receivers of the information must perceive the message as a threat or barrier related to themselves or someone/something they care for (Nabi, 1999). Similar arguments were made from previous scholars, arguing that when individuals recognize a certain threat from a certain risk situation such as a potentially dangerous technology (Renn et al., 2021; Stern et al., 1999), or even a political party (Hibbing & Theiss-Morse, 2002; Marcus et al., 2011; Muhlberger, 2018) poses threat to other people, other species or nature (problem awareness) they are more likely to act against it. Based on this, we hypothesize that:

H5. Participants that perceive higher risks from nuclear installations will have a) more negative feelings towards decommissioning, b) will be more likely to seek information and c) more likely to participate in decision-making regarding decommissioning of NPPs.

Participation intention is also influenced by familiarity with the topic. For instance, feeling that one has sufficient information about a certain topic can make an individual feel more capable in participating in decision-making procedures (Hibbing & Theiss-Morse, 2002; Liu et al., 2021; Reichert, 2016). Pellizzoni (2003) also argued that one of the cognitive qualities making people more entitled to participate in decision-making procedures is their familiarity or expertise with a certain topic. Similarly, studies from nuclear risk communication found that participants that had higher prior knowledge were more willing to accept communicated messages and to seek more information (Perko et al., 2012; Zeng et al., 2017).

H6: The more informed participants perceive themselves to be about nuclear decommissioning, the more they are a) willing to seek information and b) to participate in decision-making procedures about nuclear decommissioning.

Interest on a certain topic is also an important factor explaining public participation intention. The CFM argues that willingness to think about a situation (in our case, willingness to read a news article about nuclear decommissioning) is an explanatory factor of the willingness to engage with the information source (Nabi, 1999). Similar arguments are raised by several other studies on participation intention which found that interest or curiosity about a certain topic influences an individual's participation intention (Hibbing & Theiss-Morse, 2002; Hoti, Perko, Thijssen, et al., 2021; Muhlberger, 2018). This leads to the following hypothesis:

H7: People that are more interested in the topic of decommissioning will be more likely to a) seek more information, and b) be willing to participate in decision-making procedures related to decommissioning.

Finally, based on studies on public participation, we also expect there to be a difference between intended and real participation intention (Ajzen, 1985; Ajzen et al., 2004; Quintelier & Blais, 2016). For instance, in political science studies, it has been found that there are issues with voting over-reporting in surveys (Belli et al., 1999). This happens for several reasons, among which, social desirability (to be viewed favorably by others), memory failure (incorrect inferences about the past), and source monitoring (confusing intention to participate with having actually participated) (Belli et al., 1999; Van Gelderen et al., 2015). The same difference has been found in other fields too (e.g. choosing renewable energy (Momsen & Stoerk, 2014), however, it has not been tested yet in the topic of nuclear decommissioning. Based on the existing arguments on this difference, we hypothesize that:

H8: Intended and actual participation intention are explained by the same variables, however, participants that received a "real" scenario concerning their participation, are less likely to participate than those that received a hypothetical scenario.

Method

Design, sample and data collection procedure

A 4x2 (4 groups testing uncertainty communication x 2 groups measuring intended versus actual participation) experiment was conducted as part of a large public opinion survey in Belgium related to perceptions and attitudes towards nuclear technologies in Belgium in 2021. The final sample had N= 1060 respondents representative for the (18+) Belgian population with respect to gender, age, level of urbanisation of the living habitat and province. Given that data was collected in the second COVID-19 lockdown in Belgium, Computer-Assisted Web Interviewing (CAWI) was used as a method for data collection. Most items in the survey were formulated as questions or statements (and were tested with a pilot study with 20 respondents beforehand), while answering categories were mostly expressed with a five points Likert-scale. The answering categories typically ranged from 'strongly disagree' to 'strongly agree', but some of them were adjusted to the context of the statement or question. The ethical approval for this experiment was issued by the ethical committee of the University of Antwerp in Belgium (dossier number: SHW_20_77).

Stimulus selection

As part of the experiment, participants were divided in 4 groups for the main independent variable, namely uncertainty communication (3 experimental groups and 1 control group). The control group received only introduction to what decommissioning of nuclear installations is. The introduction was as follows "*After they have permanently stopped producing nuclear energy, nuclear power plants must be decommissioned. This entails four steps: dismantling of the (1) installation and the (2) infrastructure, the (3) remediation and clearance of the buildings, and (4) the demolition of these buildings. After these steps, the radioactivity is only present in the form of traces.*"

Participants that belonged to the three experimental groups, on the other hand, received one type of uncertainty related to decommissioning in addition to the introduction to what decommissioning is. The CFM argues that when testing the impact of a message, it is important that respondents judge the topic relevant to themselves, their relatives or the environment (Nabi, 1999). After discussing with several experts in the field of decommissioning, we identified 3 main types of uncertainties that experts are faced with when it comes to decommissioning of nuclear installations, and that might be relevant for the Belgian population. This way, apart from introduction to decommissioning, the first experimental group received also an uncertainty about *1) public's acceptance of remaining radioactivity on the site*; the second experimental group received an uncertainty about *2) the amount of radioactive waste resulting from the decommissioning*; and the last experimental group received an uncertainty about the *3) financial constraints related to the decommissioning process.* Figure 1 is an illustration of how uncertainties were provided to participants in different groups, whereas table 1 shows the distribution among experimental groups regarding the uncertainty condition.

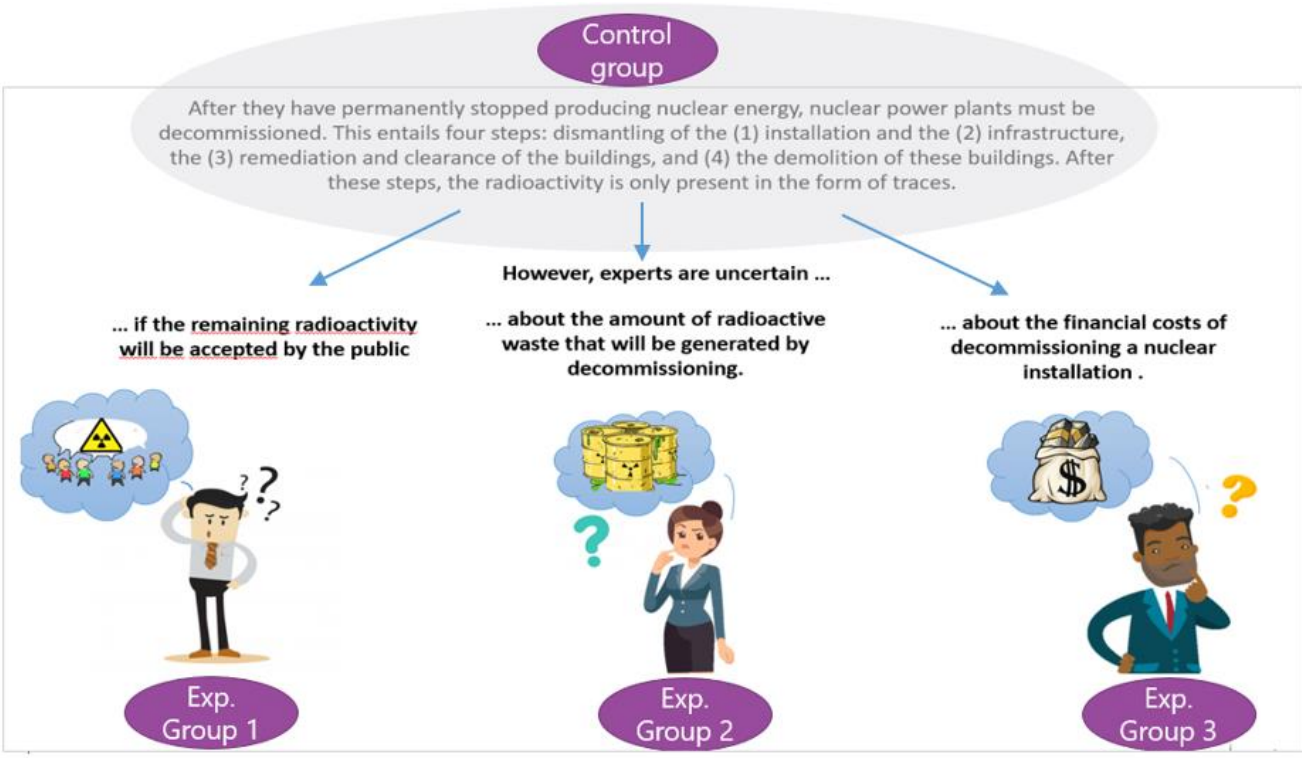

Figure 1. Introduction to decommissioning without (control group) and with (experimental groups) uncertainties as shown to survey respondents.

Table 1. Distribution among experimental groups

	Frequency	*Percent*
Control group	295	27.8%
Experimental group 1	253	23.9%
Experimental group 2	263	24.8%
Experimental group 3	249	23.5%

Variable operationalization

Dependent variable: Participation intention

Participants were additionally divided into two groups in terms of the main dependent variable: participation intention. Research shows that planned behavior differs from actual behavior (Ajzen, 1985; Fishbein, 1980; Quintelier & Blais, 2016). For instance, people may say that they are willing to participate in one form or another, but when time comes to participate, few of them actually do so. For this reason, in this study we have added a new item in order to measure respondents'actual participation intention.

In order to do so, half of the sample (N=519) received the question "***If there is an initiative*** *to involve citizens in the decision-making process concerning decommissioning of nuclear power plants in Belgium (offered at flexible dates and hours), and anybody could participate, to what extent would you like to do so?*", whereas the other half (N=541) received the question *"**Currently, there is an initiative** to involve citizens in the decision-making process concerning decommissioning of nuclear power plants in Belgium (offered in flexible dates and hours), and anybody can participate. Would you like to write your name in the list so that you can be involved in the decision-making process?".* The following answering categories, presented on a graphical card, were offered and participants could only choose one option.

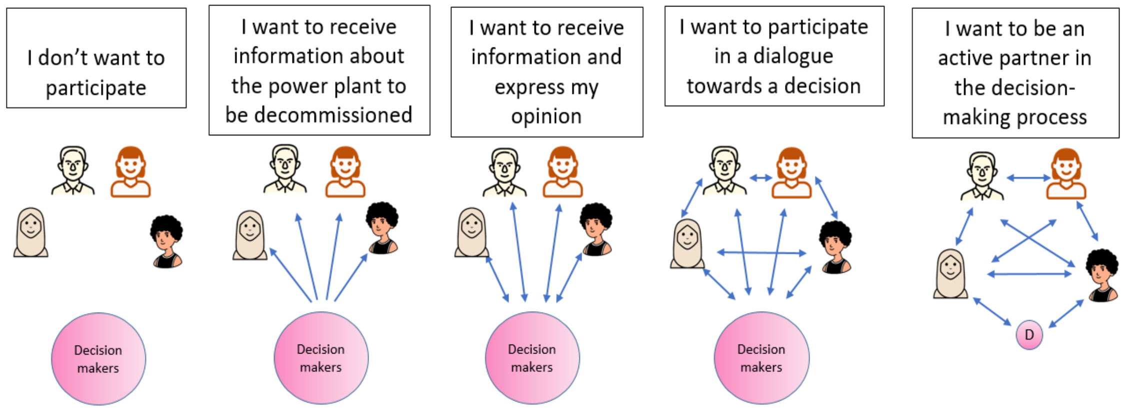

Figure 2. Answering categories indicating level of participation intention used in the Barometer survey 2021 (graphical card).

Independent variables

Uncertainty communication

As explained in the methodological section, participants were divided in 4 groups, namely 1 control and 3 experimental groups. In order to measure the effect of each type of uncertainty, we have created 3 separate variables (Unc1, Unc2, and Unc3). In Unc1, the value 1 means that the participant belonged to the 1st experimental group, receiving uncertainty public acceptance of remaining radioactivity, and 0 means that they belonged to the control group. The other groups in this variable were declared as missing. The same procedure was applied related to the other experimental groups, namely the one with uncertainty about radioactive waste and the one with uncertainty about financial constraints.

Preference for uncertainty communication

Preference for uncertainty communication was measured with one item, asking respondents to place themselves on a scale from 1) totally disagree to 5) totally agree (or 9) don't know/no answer) with the statement "I want to be informed about the decommissioning of nuclear installations even if some aspects are uncertain."

Attitude towards participation

To measure attitude towards participation, we asked respondents to use a scale from -3 to +3 to indicate their opinion about their participation in the decision-making process concerning decommissioning of nuclear power plants in Belgium. This was measured with 3 items similar to (Hoti, Perko, Thijssen, et al., 2021), namely "I believe that my participation in this decision-making process is 1: -3) Pointless to 3) Worthwhile; 2. -3) Uninteresting to 3) Interesting; and 3. -3) Disappointing to 3) Rewarding. Reliability test among these three variables shows an alpha value of 0.865. For the analysis, we conducted a Principal Component Analysis (PCA) with these variables in order to have one factor. This factor explains 79% of the variance and has a Kaiser-Meyer-Olkin (KMO) value of 0.728. Table 2 shows the factor loadings.

Table 2. Factor loadings for the attitude towards participation factor

	Component 1
Pointless-Worthwhile	0.894
Disinteresting-Interesting	0.906
Dissapointing-Rewarding	0.862

Risk perception

Participants' risk perception concerning decommissioning was measured with one item, asking participants "How do you perceive the potential risk to your health from nuclear power plants after they stop producing nuclear energy?". The answering categories ranged from 1) no risk at all to 6) very high risk and 9) don't know/no answer. We used the term "nuclear power plants after they stop producing nuclear energy" to make it more understandable for respondents given that the term decommissioning may sound a bit more technical.

Perceived level of information

To measure participants perceived level of information, we asked them "To what extent do you consider yourself to be informed about what happens with a nuclear power plant after it has permanently stopped producing nuclear energy?". Answering categories ranged from 1) uninformed to 5) very well informed and 9) don't know/no answer.

Interest on the topic of decommissioning

Interest in the topic of decommissioning was also measured with one item. We asked participants "If you saw a news article related to what happens with a nuclear power plant after it permanently stops producing nuclear energy, would you take the time to read it?". The answering options ranged from 1) definitely not to 5) definitely yes, and 9) don't know/no answer.

Mediating variables

For the mediating effects we focus on 3 variables, namely 1) subjective feeling of worry versus tranquility, 2) subjective feeling of pessimism versus optimism, and 3) information seeking behavior. We choose these three variables as mediating ones because according to the CFM, uncertainty communication can influence feelings, which in turn influences information-seeking behavior and finally also participation intention (Nabi, 2002).

Subjective feelings

To measure participants' feelings towards nuclear decommissioning, we asked them "*To what extent does decommissioning of nuclear power plants evoke the following feelings in you, if at all?".* There were 2 items where they had to slide the cursor from -3 to +3. The first item was (-3) Worry to (+3) Tranquility, whereas the second item was (-3) Pessimism to (+3) Optimism. Given that nuclear decommissioning is not a "hot" topic in Belgium yet, people do not have strong feelings about it. For this reason, we chose these two types of feelings that we evaluated to be more appropriate in this case rather than stronger feelings such as fear or anger.

Information seeking behaviour

Finally, information seeking behaviour was also measured with one item. Participants had the option to choose from 1) strongly disagree to 5) strongly agree (or choose the option 9) don't know/no answer) with the statement "I tend to actively seek out information about health effects of radiation. We decided to focus on the overall health effects of radiation in order to capture a broader information seeking behavior rather than specifically focus on nuclear decommissioning.

Results

To test our hypotheses, we conducted a Confirmatory Factor Analysis in Structural Equation Modelling (SEM) by using the Mplus software. SEM is a multivariate technique which combines aspects of factor analysis and multiple regression to allow for testing series of inter-connected causal relationships (Hair et al., 2010; Hoti, Perko, Thijssen, et al., 2021). Given that the nature of our hypotheses requires testing them in a series of order, and testing for mediation analysis, this type of analysis was the most appropriate one.

We first test the model with the variable participation intention with a hypothetical scenario, as this was the variable used throughout the years to measure public participation intention in SCK CEN Barometers (Hoti, Perko, Thijssen, et al., 2021; Latré et al., 2018; Turcanu et al., 2014). As can be seen in figure 3, the model fit for this tested model is very good, with a Comparative Fit Index (CFI) of 0.946 (a good model should have a value of 0.90 or higher), a Root Mean Square Error of Approximation (RMSEA) of 0.04 with a 92% chance that the RMSEA is below 0.05. The explained variance for this dependent variable is 42%.

Based on our first hypothesis we expected participants that receive uncertainty communication to be more likely to a) seek information and consequently to b) be willing to participate in decision-making procedures related to nuclear decommissioning than those in the control group. Our results show that this is not the case. Uncertainty communication neither has a direct effect on participation intention, nor an indirect one, through information seeking behavior. Based on this, we reject hypothesis 1a and 1b.

Our second hypothesis (H2a and H2b), though, is confirmed from our results, given that we found that participants that prefer to receive information about decommissioning even if some aspects are uncertain are more likely to seek more information about health effects of radiation as well as more likely to be willing to participate in decision-making procedures about decommissioning.

Then, we tested the mediating effect of feelings on the causal linkage between uncertainty communication, information seeking behavior and participation intention. Here we see an interesting pattern. Of the three experimental groups, the group that received uncertainty about the amount of radioactive waste, and the group that received uncertainty about the financial cost reported slightly (but significant) more negative feelings (i.e. worry and pessimism). This means that uncertainty communication indeed influences negative feelings, but it also depends which types of uncertainties are mentioned. In our experiment, public acceptance of remaining radioactivity did not have any significant effect, whereas the other two did. The causal chain breaks here though, as based in our model, these feelings do not have a significant impact on information-seeking behavior and consequently also not in participation intention.

Apart from uncertainty communication, we also had another set of variables with potential impact on feelings, information seeking behavior and participation intention. Results show that indeed attitude towards participation positively influences information seeking behavior as well as public participation intention, which means that participants that have a more positive attitude towards participation, are more likely to seek information about health effects of radiation and also more likely to participate decommissioning-related decision-making procedures.

Risk perception, on the other hand, influences all three consequential variables, namely feelings, information seeking behavior and participation intention. Based on our results from figure 3, participants that perceive higher risk from nuclear decommissioning, are more worried and pessimistic about decommissioning, are more likely to seek information and also to take part in decision-making. This confirms our hypothesis H5 (a,b, and c).

We also hypothesized (H6a and H6b) that participants that perceive themselves to be more informed about nuclear decommissioning are more likely to seek even more information and also to take part in decision-making procedures. This appears to be true for the first part, meaning that higher perceived level of knowledge leads to higher information-seeking behavior, but it does not hold for the second part, namely for its impact on participation intention. Surprisingly, public participation intention is not directly influenced by the level of perceived knowledge, but there is an indirect effect, through information-seeking behavior. The level of perceived knowledge also has a significant positive effect on feelings, meaning that participants that perceive themselves to be more informed about nuclear decommissioning are more tranquil and more optimistic about this issue.

Finally, we also tested the impact that interest on the topic of decommissioning has on information-seeking behavior (H7a and H7b). Results show that indeed, participants that were more interested in the topic of decommissioning had higher information-seeking behavior. However, there was no direct effect of interest on participation intention, only indirectly, through information-seeking behavior.

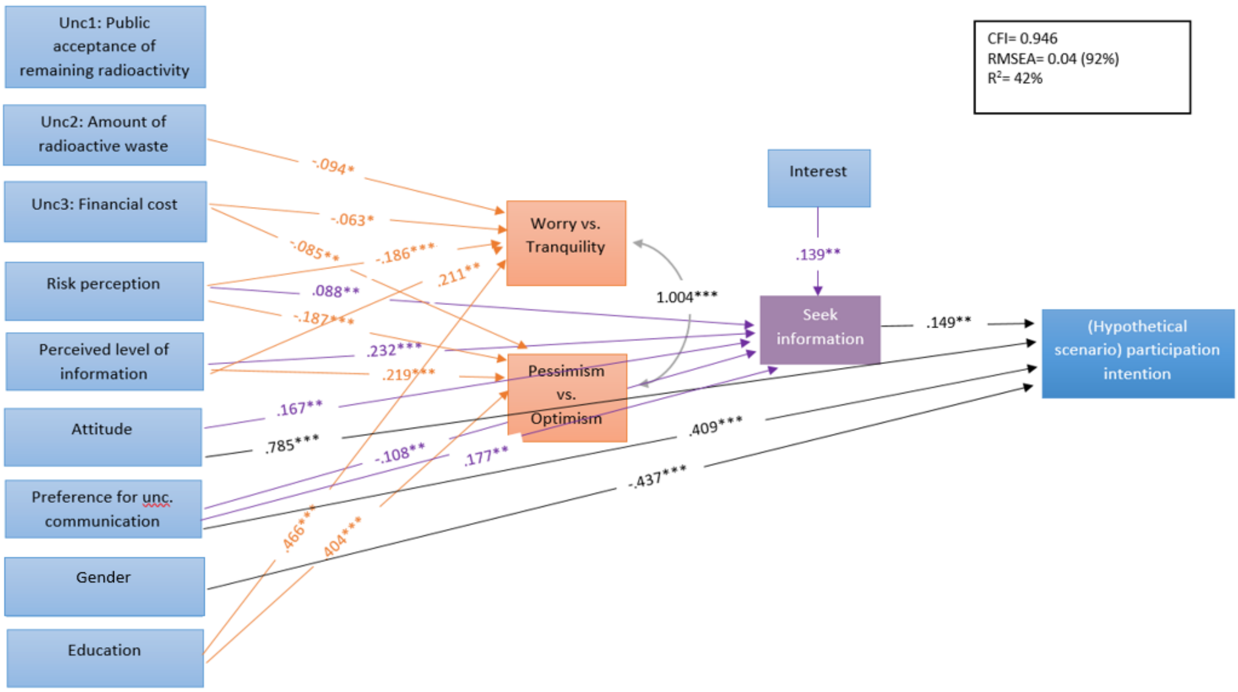

Figure 3. Path diagram with hypothetical scenario of participation intention. Only significant effects are shown.

In our last hypothesis (H8) we pointed to the expectation that intended and actual participation intention are explained by the same variables, however, participants that received a "real" scenario concerning their participation, are less likely to participate than those that received a hypothetical scenario. Descriptive results (figure 4) show that indeed, when we ask respondents to participate in a "real" initiative that is "happening now", they are much less willing to participate. 38% of the respondents said that they do not want to participate at all (in comparison with 22% in the hypothetical scenario), 19% said they want to receive information only (24% in the hypothetical scenario), and only 32% opted for more active forms of participation (in comparison with 45% in the hypothetical scenario).

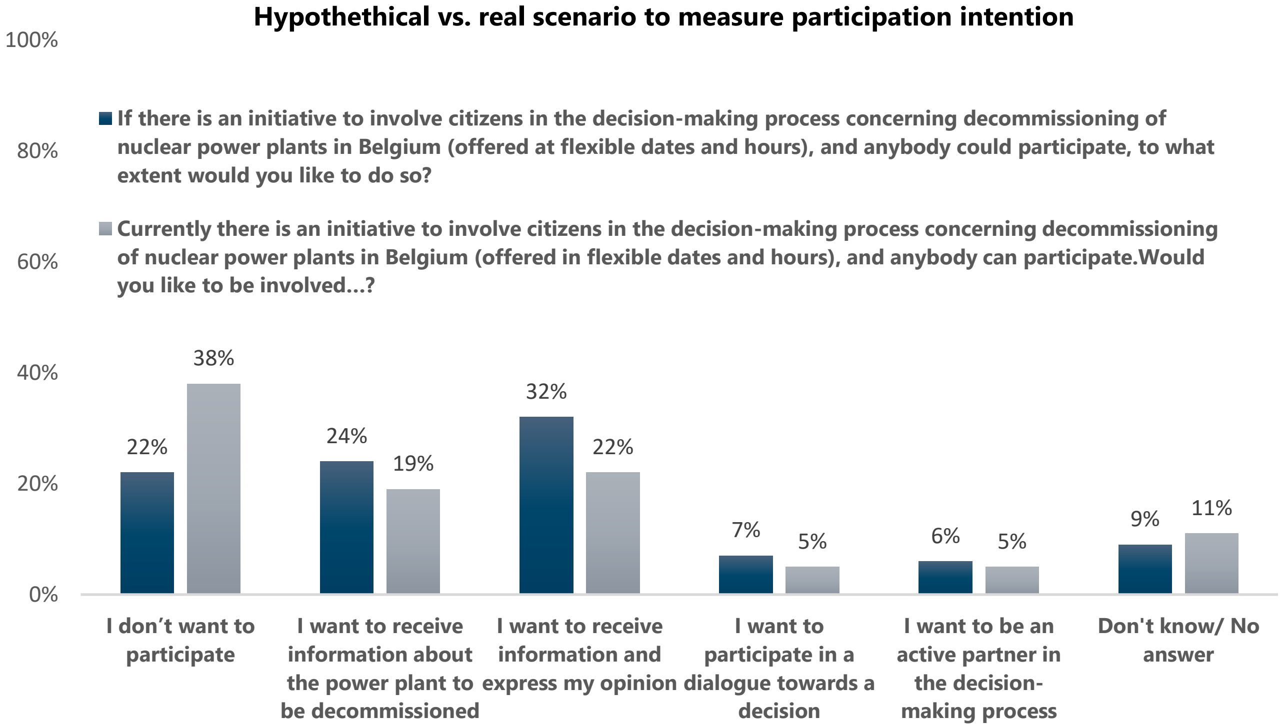

Figure 4. Public participation intention measured with a real vs. hypothetical scenario. (N= 1060), sample weighed for gender, education, age, province, region and habitat.

To test whether there are differences in what influences actual participation intention, as a next step, we ran the same CFA in Mplus only changing the dependent variable, which now is the question of whether respondents want to participate in a decision-making procedure about nuclear decommissioning that is "currently happening". As can be seen in figure 5, the direct and indirect effects for all variables are the same between both scenarios (comparing it with figure 3). The only difference is that in comparison to intended participation, actual participation intention is not influenced by information seeking behavior, but it is directly influenced by perceived level of knowledge. This means that participants that perceive themselves to be more knowledgeable about decommissioning are more likely to participate when asked to do so in a procedure that is currently happening. Uncertainty communication did not influence actual participation either.

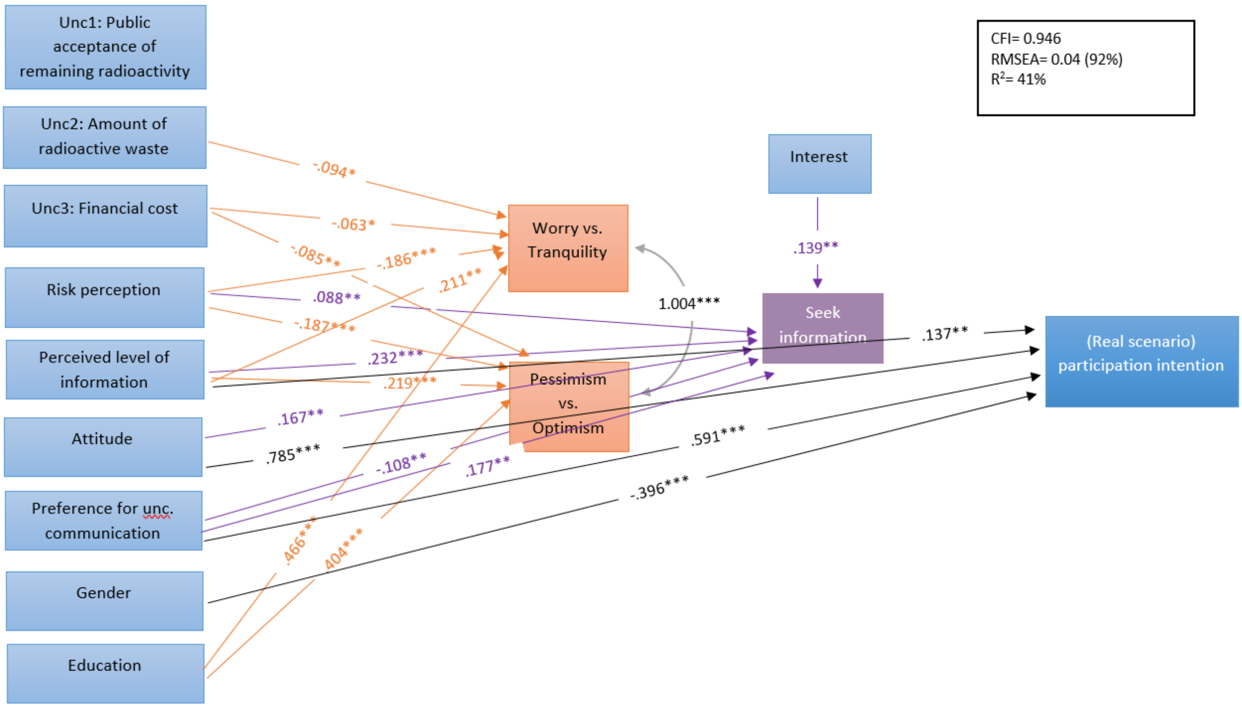

Figure 5. Path diagram with real scenario of participation intention. Only significant effects are shown.

Discussion

By means of a survey embedded experiment, this article analyzes the impact that uncertainty communication has on feelings, information seeking behavior, and public participation intention in decision-making related to decommissioning of nuclear installations in Belgium.

While Europe's nuclear reactor fleet is ageing, the number of completed projects of decommissioning of nuclear installations is negligible (Invernizzi et al., 2017). This makes the process of applying lessons from the past related to the financial, economic, and social aspects more difficult and increases challenges with public trust, risk perception, and attitudes (Invernizzi et al., 2017; Perko et al., 2019). This is why, in an attempt to address the social aspects of decommissioning of nuclear installations, it is advised that the public is involved in decision-making related to it. Participation in such decision-making procedures provides citizens with the opportunity of learning about the technical and political facets of decision-making options and enables them to discuss, co-decide, and evaluate these options and their likely consequences according to their own set of values and preferences (Pellizzoni, 2003; Renn, 2008). Previous research on public participation in decision-making procedures related to decommissioning of nuclear installations, though, shows that the willingness to participate is rather low, with interest on the topic, risk perception, and familiarity or perceived knowledge being the main explanatory variables (Hoti, 2022; Hoti, Perko, Thijssen, et al., 2021). This is why, in this article we tested whether telling participants that even experts are uncertain about some aspects of decommissioning would influence their participation intention. We test this via a causal chain of feelings and information seeking behavior as mediating variables.

Several studies have tested the impact of different formats of uncertainty communication (Doyle et al., 2014; Hart et al., 2019; Knoblauch et al., 2018; Maxim et al., 2013; Van Der Bles et al., 2019). What has not been tested so far, however, is whether different types of uncertainties can have different effects among the information receivers. We addressed this gap by testing the impact of communication of three types of uncertainties related to decommissioning of nuclear installations, namely, 1) uncertainties about public acceptance of remaining radioactivity, 2) the financial cost, and 3) the amount of radioactive waste.

Results show that, contrary to our first hypothesis, uncertainty communication did not have a significant impact on information-seeking behavior and participation intention. Still, as expected from our second hypothesis, those participants that preferred to receive information about decommissioning even if some aspects are uncertain, were more likely to be willing to seek information and participate in decision-making procedures about decommissioning. This indicates that while communicating uncertainties does not necessarily trigger information receivers to seek more information about decommissioning or be engaged in decision-making procedures about it, they still expect and want to receive information about existing uncertainties.

Our results also showed that communication of some types of uncertainties, namely, uncertainties about the financial costs, and about the amount of radioactive waste produced by decommissioning, slightly increases negative feelings such as worry and pessimism. However, it is important not to generalize among the audiences, since, as can be seen in figure 4 and 5, certain variables such as education, risk perception and perceived level of information also have a strong effect on these feelings. This means that if we take certain groups of the public out (e.g. participants with lower education, higher risk perception, and lower perceived knowledge), the results would drastically change. One reason why we found that uncertainty communication leads to negative feelings could be the fact that in this study we have framed uncertainties as “uncertainties that experts are faced with”. One study that reviewed the impacts of uncertainty in science communication found that experiments that portray uncertainty as “consensus uncertainty” or disagreement/conflict in science, are much more likely to find negative effects on feelings than experiments that portray uncertainty as “error ranges and probabilities” (technical uncertainties) (Gustafson & Rice, 2020: 614). Furthermore, we also found that feelings did not act as a mediating variable between uncertainty communication and participation intention, which leads us to reject hypothesis 3. A reason for this could be that in this study we used two types of feelings that might not be as strong or impactful for information-seeking behavior. Previous studies have found that stronger feelings such as threat or fear have stronger effects to leading to action (Marcus et al., 2011; Nabi, 2002). Furthermore, feelings of worry, that we have measured in this study, have the potential to generate the “freeze” approach among information receivers, making them shrink from action (Renn et al., 2021), which can be a reason why there was no significant effect of the feelings we measured and information-seeking behavior and participation intention. We therefore recommend future studies to test other and/or stronger types of feelings and their impact on participation intention.

In addition to the previous results, the findings show that when it comes to public participation, the relationship is not that simply A leads to B, but there is rather a whole set of inter-related variables involved. For instance, we found that several factors such as attitude towards participation, risk perception, perceived level of information and interest on the topic have either direct, indirect, or both-ways effect on participation intention. More specifically, attitude towards participation influences participation intention strongly directly, as well as indirectly, through information-seeking behavior. Risk perception and perceived level of knowledge influence participation intention only indirectly, with those participants that have higher risk perception and higher level of perceived knowledge being willing to seek more information and be more willing to participate. Finally, interest on the topic of decommissioning also influences participation intention indirectly, through information-seeking behavior. This way, we confirm hypothesis 4, 5, 6, and 7.

Finally, we hypothesized there to be a difference between intended versus actual willingness to participate in decision-making procedures. Results show that there is indeed a difference between the two, with participation intention being much lower in a real scenario in comparison to a hypothetical one. This means that intention to participate is not a given and that a crucial element is participation intention is still rather low, even when people are given the opportunity to participate. However, in comparison to previous years, reports on participation intention related to decommissioning of nuclear installations shows there to be a progress on public's willingness to participate (Hoti, Perko, & Turcanu, 2021). This is why it is important to continue testing ways to increase public participation intention, as well as ways that ensure that these participation procedures are balanced and equal both, in the recruitment, as well as in the participating/decision-making procedures.

Conclusion

This study tested the impact of uncertainty communication on public participation intention directly, and indirectly, through feelings and information-seeking behavior. It does so by using data from a survey embedded experiment with N=1060 respondents from a representative sample of the Belgian population, and by using decommissioning of nuclear installations as a topic for uncertainty communication.

Findings show that uncertainty communication influences neither information-seeking behavior, nor participation intention. It does slightly influence, though, negative feelings of worry and pessimism. But does this mean that information providers should not include uncertainty in their communication? Certainly not. We argue that while uncertainty is not going to reduce negative emotions immediately, long term uncertainty information and familiarity with uncertainties will give assurance and comfortability with uncertainty information. Previous studies have found that uncertainty communication does not influence the feelings and emotional arousal of people that are more familiar with uncertain results and processes, as well as are encountered with uncertainties in the nuclear field on a more frequent basis (Hoti, 2022). Furthermore, in this current article we found that the majority of the respondents (62%) would like to receive information about decommissioning even if it contains uncertainties. Based on these findings we argue that uncertainty should be involved in scientific communication, and the more people are encountered with uncertainty communication, the more comfortable with it they will feel.

We also recommend future research to test different types of feelings when it comes to the causal chain between uncertainty communication, feelings, and public participation intention. Finally, we also recommend future research on this topic to test different ways of uncertainty communication, and different framings of uncertainties.

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Disclosure

The authors report that there are no competing interests to declare.

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Chapter 6: The impact of uncertainty communication on emotional arousal and participation intention: The psychophysiological effects of uncertainties on experts

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Abstract

Research related to uncertainty communication remains contradictory, with some authors providing arguments of why it should be communicated, whereas others arguing that we should not do so. Practically, though, the decision on whether or not to openly communicate uncertainties remains on the level of experts of a certain field. That is why, in this article we analyze the psychophysiological reaction of experts when exposed to uncertainty and we do so by focusing on the topic of nuclear decommissioning (a salient issue, in which many uncertainties prevail) and using a sample of N= 134 participants which are employees of nuclear-related institutions in Belgium (divided in 2 groups: familiar and unfamiliar with decommissioning).

By using the Uncertainty Reduction Theory (URT) and Uncertainty Management Theory (UMT), we study for the first time 1) whether communicating uncertainty influences participation intention directly, and 2) whether this impact is mediated by emotional arousal. The method consists of an experimental design, combining a survey with psychophysiological measurement of emotional arousal.

Results show that participation intention is directly influenced by attitudes towards participation, moral norm and time constraints, whereas familiarity with the topic of decommissioning influences participation intention indirectly, through attitude towards participation. Uncertainty communication, our main variable of interest, does not influence participation intention. It does influence, though, emotional arousal (concerning the public acceptance of the remaining radioactivity resulting from decommissioning), but it does not generate negative feelings such as anger or fear. Given that in the literature there is a debate on whether or not uncertainties should be communicated, the findings of this study imply that the concern that uncertainty communication leads to negative feelings should not be used as a reason not to communicate uncertainty anymore. Further implications and limitations are discussed in the article.

Keywords: Uncertainty communication; participation intention; emotional arousal; nuclear decommissioning

Introduction

Uncertainties regarding the effects, costs, and collateral damage of technological interventions have recently come to the center of scientific discussion (Yeh & Rubin, 2012). While some topics such as climate change (Visschers, 2018) or nanotechnologies (Retzbach, Marschall, Rahnke, Otto, & Maier, 2011) have put much more emphasis on analyzing the impact of uncertainty communication, very little is known about the impact of uncertainty communication on public participation intention and the role of psychophysiological mediators such as emotional arousal. In order to address this gap, this paper will focus on the impact of communication of uncertainties with regards to the highly salient issue of the decommissioning of nuclear installations.

Decommissioning is a good example since it is a complex issue in full development. Notably, it is now a pertinent energy-related matter since most of the nuclear reactors built during nuclear renaissance will soon reach the end of their operational life (Hoti, Perko, Thijssen,

& Renn, 2021). Furthermore, given that decommissioning is a long and complex process which can take decades to be completed, many uncertainties about future consequences prevail. Even if the decommissioning plan has been considered as early as the design stage of the facility, it means that the situation has to be anticipated decades ahead, leading to substantial uncertainties about the future state (OECD/NEA, 2003). It has been argued that nuclear decommissioning projects are also ethically problematic especially when we look at it from an intergenerational perspective. While the main benefits of nuclear power production are for the present generation, most of the burdens (e.g. radioactive waste) are *ipso facto* largely transferred to the future generations (Taebi, 2012).

These arguments point to the relevance of social aspects connected to decommissioning processes. Given that in the upcoming years it is expected that more than 100 additional nuclear facilities will be decommissioned (Nuclear Energy Institute (NEI), 2019), in order to address the social aspects of decommissioning, it is now required from various regulations (such as the European Council Directive 2011/92/EU; the amended Environmental Assessment Directive 2014/52/EU; and the Aarhus Convention) that the public should be involved in decision-making related to it. Not only is public participation in decision-making procedures legally required, it is also highly recommended by various scholars as it enhances social acceptance of pre-defined solutions; gives communities a say on the matter (Hietala & Geysmans, 2020); may decrease conflict and increase trust in science; legitimizes processes of environmental assessment; and allows to benefit from mutual learning (Stern & Fineberg, 1996).

Given this relevance of public participation in decision-making procedures, many studies have recently analyzed public's willingness to participate in nuclear-related decision-making procedures, where they found that different aspects such as interest on the topic, radiological risk perception, attitudes towards participation and moral norm (Hoti et al., 2021; Turcanu, Perko, & Laes, 2014) influence participation intention. Nothing is yet known, though, about the impact that uncertainty communication can have on public participation intention related to decommissioning. Scholars argue that a precondition for a decision to be well-founded is that scientific experts point out all decision-relevant uncertainties (Levin, 2006). Similarly, Newig, Pahl-Wostl, & Sigel (2005) argue that uncertainty communication plays an important role on participation, where the public participates in order to manage and reduce uncertainties. In this study we want to test whether communicating uncertainties (i.e. showing that there are uncertainties about the (1) remaining radioactivity, (2) the amount of radioactive waste and (3) the financial costs) will have an impact on increasing public participation intention.

In addition to testing the impact of uncertainty communication on participation intention, we will also scrutinize the mediating role of emotional arousal in this effect. The limited research that exists on uncertainty communication consists of contradictory findings and arguments related to it. While some authors argue that uncertainties should be communicated because it reduces fear (Maxim, Mansier, & Grabar, 2013), fatalism and feelings of backlash (e.g., skepticism, worry, guilt, fear, anger, and helplessness) (Jensen, 2008; Jensen et al., 2011), others have found that including statements about uncertainty increases concern (Knoblauch, Stauffacher, & Trutnevyte, 2018; Visschers, 2018) information overload, worry or confusion (Han, 2012; Han et al., 2010; T Perko, Benighaus, Tomkiv, & Wolf, 2020). However, the majority of these arguments remain theoretical in nature, given that very few of them are empirically tested, and even in these cases, emotions and feelings are tested with self-reporting questions only. Furthermore, the impact of emotional arousal as a mediator ultimately explaining behavior has not yet been tested in this context. By building on these studies, we intend to contribute to the scientific literature on uncertainty communication by using psychophysiological measurement of emotions. Research shows that psychophysiological measurement of arousal is a useful complement to self-report measures, with studies demonstrating that neural activity can predict variability in behavior change that is not predicted by subjective measures (Falk, Berkman, Whalen, & Lieberman, 2011).

To sum up, the goals of this study are to test 1) whether communicating uncertainty has a direct impact on participation intention and also 2) whether this impact is mediated by emotional arousal. By analyzing these effects, this study contributes to research on uncertainty communication by addressing two main research gaps. First, it contributes to the lack of research on the impact of uncertainty communication on public participation intention, and second, on the impact that uncertainty communication can have on emotional arousal by means of psychophysiological measurement.

Theoretical argument

There are a number of different theories focusing on explaining how people react and behave in situations accompanied with uncertainty (Bradac, 2001; Brashers, 2001; Lipshitz & Strauss, 1997; Van Bree & Van Der Sluijs, 2014). Two of the most prominent theories in the uncertainty communication literature are the Uncertainty Reduction Theory (URT) (Bradac, 2001) and the Uncertainty Management Theory (UMT) (Brashers, 2001; Brashers, Goldsmith, & Hsteh, 2002; Brashers, Hsieh, Neidig, & Reynolds, 2006).

Uncertainty reduction theory argues that individuals routinely tend to reduce uncertainty by seeking more information (Anthony & Sellnow, 2016; Bradac, 2001). Uncertainty makes people more uncomfortable, and therefore they are more likely to be willing to seek information, in order to reduce those uncertainties (Babrow, 2001; Babrow, Kasch, & Ford, 1998; Bradac, 2001). This effect is rooted in the idea that gaining more knowledge by taking action will ultimately lead to less uncertainty (Van ’t Klooster & Veenman, 2021). In line with the uncertainty reduction theory, Walker & Walsh (2012) argue that by injecting uncertainty at particular situations, Rachel Carson in her influential book *Silent Spring* used scientific uncertainties to engage and motivate the public to be active on environmental movements, pointing out the considerable role that uncertainty can play in public participation on various topics of concern. Based on these arguments, we expect that communicating about the uncertainties that experts are faced with regarding decommissioning, will have a direct impact on people’s willingness to participate in decision-making procedures in order for them to reduce uncertainty and gain more information on the process of decommissioning. This way, we hypothesize that:

*[H1]: Respondents that will receive introduction about decommissioning of nuclear installations which contains **uncertainty information**, will be more likely to be willing to participate in decision-making procedures than those respondents that will receive introduction text only.*

*[H1a]: Participants with high **intolerance for uncertainty** (e.g. being frustrated when not having all the information they need) will be more likely to participate in decision-making procedures concerning decommissioning.*

Additionally, Uncertainty Management Theory argues that people perceive uncertainty in different ways, not necessarily as only something that makes them uncomfortable and needs reduction (Bradac, 2001; Brashers, 2001; Brashers et al., 2002). This theory argues that although people quite often do want to reduce uncertainty, this is not the only response strategy to such situations. There are situations where uncertainty is seen as an opportunity for an individual to downplay the relevance of the matter at hand despite, or because of, uncertainty (Brashers, 2001). For instance, in the case of climate change, the presence of uncertainty in science has caused respondents to be less concerned about climate change and less likely to act on it (Visschers, 2018). Based on this theory, people judge the meaning of an event based on the impact it has on their emotions and based on their relevance to their lives (Brashers, 2001; Folkman, 2013). When uncertainty is perceived as a danger or a threat there will be a negative emotional response. For instance, uncertainty can cause anxiety and worry if it threatens health and safety (Brashers, 2001). On the other hand, it can result in a positive emotional response if it raises feelings of hope or optimism (Brashers, 2001; Brashers et al., 2002). For this reason, the authors behind uncertainty management theory urge research on uncertainty communication to focus on three connected areas, namely, (1) the experience and meaning of uncertainty, (2) emotional responses to uncertainty, and (3) corresponding behavioral interventions. Based on this theory, we hypothesize that:

[H2]: The impact of uncertainty communication on participation intention is mediated by ***emotional arousal****, with higher arousal leading to higher participation intention.*

[H2a]: Uncertainty communication will lead to higher participation intention if it induces ***(self-reported) feelings of anger and worry*** *(as opposed to calmness and tranquility) among participants.*

Familiarity with the topic has also been found to have an effect on participation intention (Sabherwal et al., 2021). For instance, people familiar with environmental conditions (Eden, 1996), or even with just the Greta Thunberg figure (Sabherwal et al., 2021) are more likely to get engaged on climate activism. Furthermore, due to their familiarity or expertise in a specific field, experts are expected to make better evaluations than others when it comes to the severity of the uncertainties (Renn, 2008). This might make participants that are more familiar with the topic of decommissioning to feel more capable in participating in decision-making procedures concerning decommissioning. Pellizzoni (2003) also argued that one of the cognitive qualities making people more entitled to participate in decision-making procedures is their familiarity or expertise with a certain topic. Based on this, we hypothesize that:

[H3]: Being ***familiar with the topic of decommissioning*** *leads to higher participation intention.*

Existing research on participation has shown that trust in experts and/or decision-makers is another important predictor of participation and should therefore be considered in this study. For instance, given that experience with fully decommissioned projects is still low, people must rely on their judgements about whom to trust (Freudenburg & Pastor, 1992). People that do not trust decision-makers, are more likely to participate in the decision-making process (Hoti et al., 2021; Neblo, Esterling, Kennedy, Lazer, & Sokhey, 2010; Turcanu et al., 2014). For this reason, we hypothesize that:

[H4]: People who have lower ***trust*** *that a) experts, b) nuclear industry, and c) nuclear safety authority (FANC) will take good decisions about decommissioning, are more likely to be willing to participate in such decision-making procedures themselves.*

One of the main theories used to explain participation intention is the Theory of Planned Behaviour (Ajzen, 1991). Some of the factors explaining participation intention used by this theory are moral norm and time constraints (Ajzen, 1991; Henningsson et al., 2015; Turcanu et al., 2014). Moral or personal norm is the belief that it is one's civil duty to participate in decision-making procedures. Time constraints indicate that a participant does not have sufficient time to participate in such procedures. A study from Turcanu et al. (2014) on public participation intention concerning nuclear research installations found that both of these items have a significant effect on participation intention. Similar findings result also from a study conducted one year later on public participation in road-planning processes (Henningsson et al., 2015). Based on these results we hypothesize that:

[H5]: Participants that ***believe that participating in decision-making procedures is their civic duty****, will be more likely to participate.*

[H6]: Participants who ***have severe time constraints*** *will be less likely to participate.*

Finally, attitude towards participation in general has been found to be a strong predictor of participation intention. People who believed that their participation in decision-making procedures was worthwhile, rewarding, and interesting, were more likely to participate (Turcanu et al., 2014). Similar findings resulted from other studies as well, where attitude towards participation was one of the main predictors of participation intention (Ajzen, 1991; Henningsson et al., 2015; Sheppard, Hartwick, & Warshaw, 1988). This leads to the final hypothesis of this study, namely:

*[H7]: Participants that have a more positive **attitude towards their participation** in decision-making procedures concerning decommissioning are more likely to be willing to participate.*

Method

Design, sample and data collection procedure

Prior to conducting the experiment, a pilot study with 10 respondents (master and doctoral students of University of Antwerp in Belgium, mainly unfamiliar with nuclear-related topics) was conducted in order to evaluate and improve the adequacy of our planned method and procedure. Afterwards, we continued with the main experiment whose design consisted of manipulating the information related to decommissioning (with uncertainty and without uncertainty). Participants were randomly selected into control or experimental group receiving different introductions to decommissioning.

When decisions are based on science, decision-making about uncertainty communication lies to a major extent in the hands of the scientific experts given that they are the ones that provide the expertise and the results to policy-makers and potentially also to the public (Morss, Demuth, Bostrom, Lazo, & Lazrus, 2015; Walker, Harremoes, Van Der Sluis, & Jannsen, 2003). For this reason, the sample of this study consists of respondents who work in nuclear-related institutions, which are expected to have a higher expertise and familiarity with nuclear decommissioning in comparison to the general public. More specifically, the sample consists of N=134 employees of the Belgian Nuclear Research Centre (SCK CEN); VITO (an independent Flemish research organization in the area of clean technology and sustainable development); and Belgoprocess (company responsible for the safe processing of radioactive waste produced in Belgium). Although they all work in nuclear-related companies, the sample still allows for comparison between familiar and unfamiliar-with-decommissioning participants as not all of our respondents were experts regarding decommissioning. These companies have employees from a wide range of fields including social sciences. A clearer description of the expertise of our participants as well as the division concerning familiarity/unfamiliarity with decommissioning is explained in subsection 4.2.2.

Participants were randomly selected during their the annual medical examination. Every year, SCK CEN, VITO and Belgoprocess employees have to undergo medical examination. This is done at different time-frames for each employee. After agreement with the medical team at SCK CEN, we decided that after the medical exam, the medical team informs the employees about our study by giving them the information and encourages them to voluntarily participate by giving out the information sheet. Afterwards, if the employees chose/had time to participate, they voluntarily came to the room where we conducted the study. The study was evaluated and approved by the research ethical committee of University of Antwerp with reference number SHW_20_105.

Data were collected in January 2021 under strict Covid-19 protective measures. Participants completed the survey one at a time. After they entered the room where the study was being conducted, they had to fill-in a survey in our computer in a software called iMotions. While filling-in the survey, the participants had a Galvanic-Skin-Response (GSR) device in their left hand. This device measured the electro dermal activity (EDA) of the participants throughout the survey, which records the electrical signal by electrodes applied to the skin. The psychophysiological data were simultaneously collected in the iMotions software together with the survey data. We were mainly interested in the tonic signals that result from sympathetical neuronal activity. EDA is has been proven to be the most useful index of emotional arousal as it is the only autonomic psychophysiological variable that is not contaminated by parasympathetic activity (Braithwaite, Watson, Robert, & Mickey, 2013; Caruelle, Gustafsson, Shams, & Lervik-Olsen, 2019).

Participants had to fill-in a set of questions concerning various aspects related to nuclear such as their risk perception, interest towards nuclear aspects, etcetera. Each question was posed in a separate slide and depending on the question, participants either had to click on their answer, or slide the cursor to indicate their preference on scales. They also received some questions about decommissioning, but at this stage (before the stimulus) decommissioning of nuclear power plants was framed as “nuclear power plants after they have permanently stopped producing nuclear energy”. Afterwards, participants received information about what decommissioning is. The type of information they received about decommissioning depended on whether the participant was on the control group or on the experimental group. Those participants that belonged to the control group received only introduction to what decommissioning is, whereas participants that belonged to the experimental group received introduction to decommissioning plus a set of 3 types of uncertainties that experts are faced with when it comes to decommissioning. These types of stimuli are explained in the section below.

Stimulus selection

Participants that belonged to the control group received only introduction to what decommissioning of nuclear installations is. They received the following text in one separate slide: *After they have permanently stopped producing nuclear energy, nuclear power plants must be decommissioned. This entails four steps: dismantling of the (1) installation and the (2) infrastructure, the (3) remediation and clearance of the buildings, and (4) the demolition of these buildings. After these steps, the radioactivity is only present in the form of traces.*

Participants that belonged to the experimental group, on the other hand, received uncertainty communication in addition to the introduction to what decommissioning is. After discussing with several experts in the field of decommissioning, we identified 3 main types of uncertainties that experts are faced with when it comes to decommissioning of nuclear installations. These are related to 1) public’s acceptance of remaining radioactivity on the site; 2) radioactive waste resulting from the decommissioning; and 3) financial constraints related to the decommissioning process. These uncertainties were given in separate slides in order to see the impact that each type of uncertainty has on participants EDA. Each uncertainty was present on the screen for 25 seconds, which based on the pre-testing of the survey, deemed to be an adequate time for processing of the type of the uncertainty. Figure 1a, 1b, and 1c are an illustration of how uncertainties were provided to the participants of the experimental group.

After they have permanently stopped producing nuclear energy, nuclear power plants must be decommissioned. This entails four steps: dismantling of the (1) installation and the (2) infrastructure, the (3) remediation and clearance of the buildings, and (4) the demolition of these buildings. After these steps, the radioactivity is only present in the form of traces.

Figure 1a. Introduction to decommissioning shown to the control group

After they have permanently stopped producing nuclear energy, nuclear power plants must be decommissioned. This entails four steps: dismantling of the (1) installation and the (2) infrastructure, the (3) remediation and clearance of the buildings, and (4) the demolition of these buildings. After these steps, the radioactivity is only present in the form of traces.

However, experts are faced with some uncertainties related to decommissioning.

Figure 1b. Introduction to decommissioning presented to the experimental group

For instance, experts are uncertain if the remaining radioactivity will be accepted by the public.

Experts are also uncertain about the amount of radioactive waste that will be generated by decommissioning.

Figure 1c. Uncertainty stimuli that the participants of experimental group received (shown in 3 separate slides one after the other)

Variable operationalization

Dependent variable: participation intention

After presenting participants with introduction to decommissioning either with or without uncertainty (depending on the experimental group), our survey asked them the following question in order to measure their participation intention: "If there is an initiative to involve citizens in the decision-making process concerning decommissioning of nuclear power plants in Belgium (offered at flexible dates and hours), and anybody could participate, to what extent would you like to do so?"

There were five answering categories which were derived by Arnstein's ladder (Arnstein, 1969) and range from: 1- I don't want to participate; 2- I want to receive information about the plant to be decommissioned; 3- I want to receive information and express my opinion; 4- I want to participate in a dialogue towards a decision; and 5 I want to be an active partner in decision-making. Respondents could only choose one option.

Independent variables

Experimental group

As explained in the methodological section, participants were divided in 2 groups, namely control and experimental group. Those in the control group received introduction to decommissioning only (coded as 0) and those in the experimental group received introduction to decommissioning plus a set of three types of uncertainties (coded as 1). 64 participants belonged in the control group and 70 belonged in the experimental group.

Familiarity with decommissioning

Familiarity with decommissioning was measured with one item asking participants how they would describe their experience with decommissioning of nuclear installations. Answering categories ranged from*: 1) I work in decommissioning of nuclear installations (e.g. a) dismantling of the installation or infrastructure; b) remediation and clearance of the buildings; or c) the demolition of these buildings); 2) I used to work in decommissioning of nuclear installations in the past; 3) I sometimes do work that is related to decommissioning of nuclear installations; 4) I do not work in decommissioning, but I am knowledgeable about it; 5) I have no experience and no knowledge related to decommissioning of nuclear installations; and 6) Other.*

In order to divide the difference between being (or not) expert and/or knowledgeable with decommissioning, we recoded this variable into a dichotomous one where 0 meant not familiar with decommissioning (category 5) and 1 meant familiar with it (category 1 to category 4). There were 4 participants that chose “other” as an answering category. Based on their elaboration, they did research on topics related to decommissioning (e.g. radioactive waste) so they were coded as familiar with decommissioning. Based on descriptive results, 49 participants were in the “non-familiar” group, and 85 were in the “familiar” group.

Trust in various actors

Trust in various actors to make good decisions about decommissioning of nuclear installations was measured with three items, namely, trusting 1) experts, 2) nuclear industry, and 3) nuclear safety authority (FANC) to make good decisions about decommissioning. Answering categories ranged from 1. Strongly disagree to 5. Strongly agree.

Reliability scale of these items resulted with Cronbach's alpha of 0.742 and a Principal Component Analysis (PCA) resulted in a factor explaining 66% of the variance.

Table 1. PCA results regarding Trust in various actors as a factor.

Items	**Factor loadings**
I trust experts to make good decisions about the decommissioning of nuclear power plants.	.853
I trust the nuclear industry to make good decisions about the decommissioning of nuclear power plants.	.725
I trust the nuclear safety authority (FANC) to make good decisions about the decommissioning of nuclear power plants.	.861

Moral norm

Similar to (Turcanu et al., 2014), moral norm was measured with one statement, namely "It is my duty as a citizen to participate in such activities". Participants could answer from 1. Strongly disagree to 5. Strongly agree.

Time constraints

Time constraints was also mentioned with one item, namely "I do not have enough spare time to participate in such activities". Similar to moral norm, for time constraints participants could had the answering categories from 1. Strongly disagree to 5. Strongly agree.

Uncertainty intolerance

Items to measure uncertainty intolerance were developed by Carleton, Norton, & Asmundson (2007). For this study we chose 6 items with the highest factor loadings with which participants either had to disagree or agree on a 5-point scale. These were 1. Unforeseen events upset me greatly; 2. It frustrates me not having all the information that I need; 3. I can't stand being taken by surprise; 4. When I’m uncertain, I can’t function very well; 5. I always want to know what the future has in store for me; 6. I must get away from all uncertain situations.

Reliability scale of these items resulted with Cronbach’s alpha of 0.763 and a Principal Component Analysis (PCA) resulted in a factor explaining 47% of the variable, with factor loadings or higher than .5 for all items (see table 2).

Table 2. PCA results regarding Uncertainty Intolerance as a factor.

Items	**Factor loadings**
Unforeseen events upset me greatly.	.810
It frustrates me not having all the information that I need.	.520
I can't stand being taken by surprise.	.791
When I’m uncertain, I can’t function very well.	.615
I always want to know what the future has in store for me.	.517
I must get away from all uncertain situations.	.798

Mediating variables

For the mediating effects we focus on 4 variables, namely 1) emotional arousal, subjective feelings such as 2) worry/tranquility and 3) anger/calmness, and 4) attitude towards participation. We chose these ones as mediating variables, as theoretically speaking, these variables are able to explain the process through which our independent variables and the dependent one are related. More specifically, based on our hypotheses, apart from the direct effects, we expect that the dependent variables will influence these 4 mediating variables, which in turn are expected to influence participation intention.

Emotional Arousal

Emotional arousal refers to the intensity of an emotional experience (Howell, Ekman, Almond, & Bolls, 2019). In this study, we measured it with skin conductance changes, where higher skin conductance reflects increased emotional arousal (Howell et al., 2019). We compared the changes in arousal of the experimental group in comparison to the control group, as well as the changes in arousal across 3 different types of uncertainties. The device used to measure arousal, measures it in milliseconds. In order to analyze the changes in arousal, we have first turned milliseconds into seconds, and then we analyzed the arousal per each second that the participant was exposed to a certain stimulus. In order to measure changes in arousal, we have subtracted the number of arousal at the beginning of the stimulus, from the number of arousal at the end of the stimulus. This way, we have different values per each experimental group, as well as per each type of uncertainty.

Subjective feelings

In order to better interpret what the arousal among participants means, we asked them to also express their feelings subjectively. Therefore, we asked them "*To what extent does decommissioning of nuclear power plants evoke the following feelings in you, if at all?".* There were 2 items where they had to slide the cursor from -3 to +3. The first item was (-3) Worry or (+3) Tranquility, whereas the second item was (-3) Anger or (+3) Calmness.

Attitude towards participation

To measure attitude towards participation, similar to Turcanu et al. (2014) we asked respondents to use a scale from -3 to +3 to indicate their opinion about their participation in the decision-making process concerning decommissioning of nuclear power plants in Belgium. This was measured with 3 items, namely "I believe that my participation in this decision-making process is 1: -3) Pointless to 3) Worthwhile; 2. -3) Uninteresting to 3) Interesting; and 3. -3) Disappointing to 3) Rewarding.

The reliability scale for these 3 variables shows a score of higher than 0.783. The 3 variables load in one factor which explains 69.7% of the variance. All variables have factor loadings of higher than 0.8 so this means that all these variables significantly correlate with the first component.

Table 2. PCA results regarding Attitude towards participation as a factor.

Items	**Factor loadings**
Pointless vs. Worthwhile	.865
Uninteresting vs. Interesting	.810
Disappointing vs. Rewarding	.829

Results

Given that our dependent variable is an ordinal one, we conducted an ordinal logistic regression. We introduced dependent variables in 4 stages, with the first model containing only socio-demographic variables such as gender, education and age, as well as the experimental group, namely with or without uncertainty communication. As can be seen in the table 4, none of these variables have a significant impact on participation intention. This means that uncertainty communication does not lead to higher participation intention. In the second model, we added familiarity with decommissioning as an additional potential predictor. This variable does not have a significant impact on participation intention either. This effect changes though, when we add additional independent variables such as arousal, subjective feelings, uncertainty intolerance, and trust in different actors in the third model. Now, familiarity with decommissioning significantly predicts participation intention, meaning that people who are more familiar with decommissioning are more likely to participate. Additionally, uncertainty intolerance also has a significant impact, with people who have lower intolerance for uncertainty showing higher willingness to participate. In the last model, we added moral norm, time constraints and attitude towards participation as additional predictors. In the final model we see that trust has a negative impact on participation intention, indicating that people who have lower trust are more likely to participate. Furthermore, moral norm, time constraints and attitude towards participation all have a significant effect on participation intention. This indicates that participants who believe that it is their duty to participate, that have more time and that have more positive attitudes towards participation, are also more likely to participate. These effects are not that surprising, that is why we only added them in the final model. The pseudo R^2 of the final model is 0.34.

Table 3. Results of binary logistic regression with participation intention as dependent variable.

	Dependent variable: Participation intention[a]			
Explanatory variable	**Model 1[b]**	**Model 2**	**Model 3**	**Model 4**
	Estimate[c]	Estimate	Estimate	Estimate
Gender	-.737	-.592	-.331	-.325
Education	.334	.394	.835	**1.080***
Age	.116	.031	.022	-.174
Experimental group	.152	.127	.302	.229
Familiarity with decommissioning		.673	**.792***	-.065
Arousal			-.129	-.181
SF[e]: Worry vs. Tranquility			-.047	-.098
SF: Anger vs. Calmness			-.126	-.145
Uncertainty intolerance			**-.399***	-.178
Trust in different actors			-.218	-.324
Moral norm				**.540***
Time constraints				**-.431***
Attitude towards participation				**.808*****
	N= 134 Pseudo-R^{2d}= .04	N= 134 Pseudo-R^2= .0	N= 134 Pseudo-R^2= .18	N= 134 Pseudo-R^2= .34

[a] = Reference category is 1= passive or no participation
[b]Ordinal logistic regression. Link function: logit. Bold font marks significant coefficients.
[c]The estimate gives the increase in log(odds), where the odds of an event with probability *p* is defined as odds(*p*) = *p*/(1 - *p*).
[d]Nagelkerke's R2. A value closer to 1 means a better model.
[e]Subjective feelings.
*$p < 0.05$; **$p < 0.01$; ***$p<0.001$

After analyzing the direct effects, and given that some of our hypotheses included mediation effects, we wanted to see in more depth what could be the indirect or the mediating effects of certain variables on participation intention. In order to do so, we applied a Structural Equation Modelling (SEM) analysis. As explained earlier, in this model we treat emotional arousal, subjective feelings and attitude towards participation as mediating variables.

As can be seen in the path diagram below, similar to the regression analysis above, moral norm, time constraints, and attitude towards participation have direct effects on participation intention. Furthermore, uncertainty intolerance also appears to directly influence participation intention, with people who have higher uncertainty intolerance being more likely to participate. The only indirect effect is the one of familiarity with decommissioning which influences participation intention indirectly, through attitude, indicating that participants that are more familiar with the topic of decommissioning have more positive attitudes towards participation and are therefore more likely to participate.

Trust on various actors to make good decisions about decommissioning has a significant impact on subjective feelings, which suggest that participants who have higher trust, have more feelings of tranquility and calmness. It does not, however, influence participation intention in this model.

An important finding is the significant impact of uncertainty communication (experimental group) on emotional arousal which indicate that participants that were on the experimental group (received introduction to decommissioning including 3 types of uncertainties) had a higher arousal than those participants that were in the control group. Given that in the SEM model our main focus is participation intention, we opted for a more parsimonious model without including extra potential predictors or moderators of emotional arousal. In table 5 below we pay a deeper focus on this effect specifically. We also notice that psychophysiological measurement of arousal and self-reported feelings are not significantly correlated. A potential explanation of this could be that since most of our respondents are familiar with the nuclear field, they would not admit that uncertainty influences their emotions (as this would be against the role model of professionals). Yet, the psychophysiological measurement shows that mentioning uncertainty does influence their emotional arousal, indicating a mismatch between the two measurements.

As can be seen in figure 2, the model suggests a very good fit. A good model fit should meet the criteria of a Weighted Root Mean Square Residual (WRMR) of lower than 0.08, a Root Mean Square Error of Approximation (RMSEA) of lower than 0.05 and a Comparative Fit Index (CFI) of closer to 1 (Hair, Black, Babin, & Anderson, 2010; Schreiber, 2017). Our model has a CFI of 0.934, a RMSEA of 0.04 with 61% probability of RMSEA being lower than 0.05, and a WRMR of 0.752. This model has an R-square of 0.48 which means that it predicts almost half of the variance of the variable participation intention (accounting for both, direct and indirect effects).

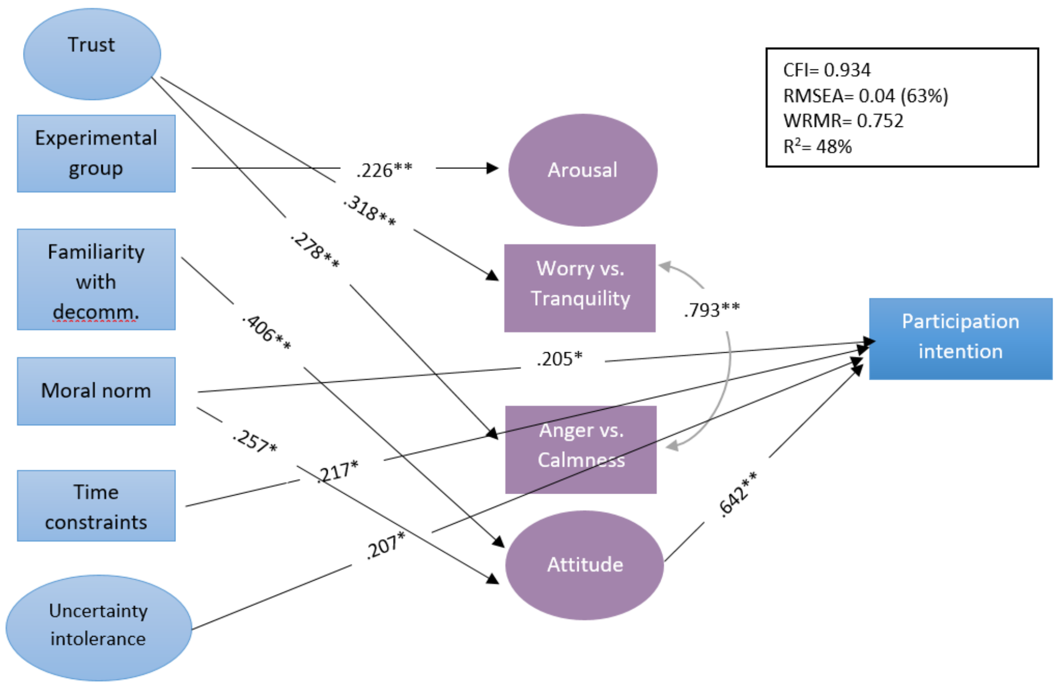

*Figure 2. SEM results including model statistics and only significant standardized pathways. *p < 0.05; **p < 0.01.; ***p < 0.001.*

As mentioned in the paragraph above, uncertainty communication led to higher arousal in comparison with the control group which did not receive uncertainty communication. We wanted to dig deeper into this and see what exactly influences this relationship. First, in figure 3 below we see that participants that were in the experimental group had indeed slightly higher arousal. Numbers 1-36 in this figure indicate the time duration it took participants to read the introduction. After they finished reading, participants had to click "next" for the next slide. The sudden drop for the control group at minute 32 can indicate the time point when they clicked "next".

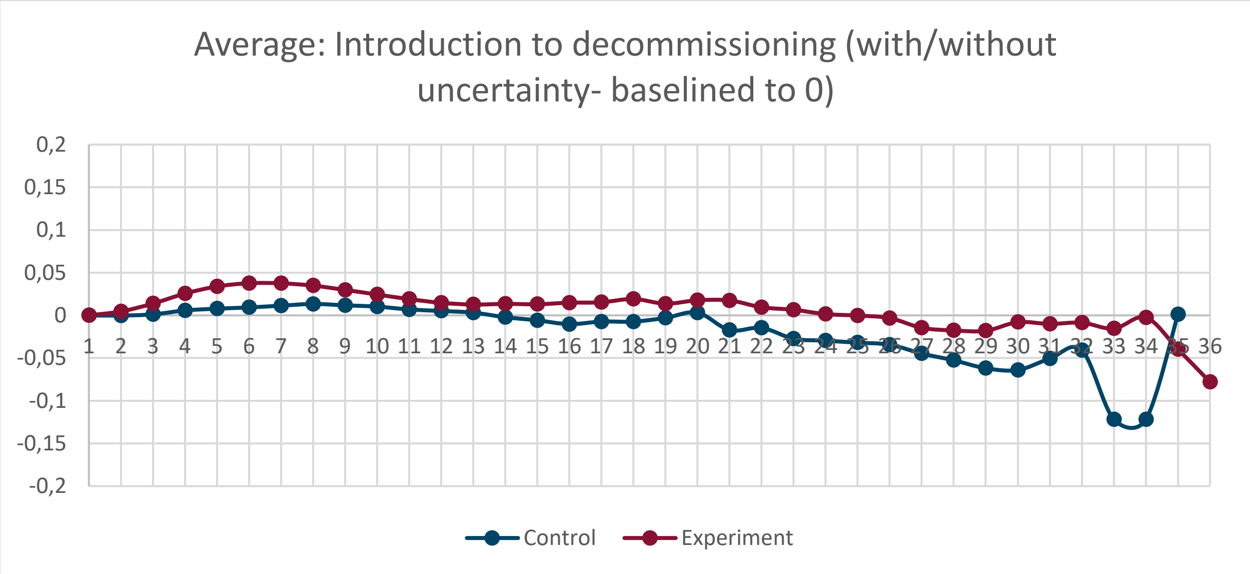

Figure 3. The difference in arousal between control and experimental group.

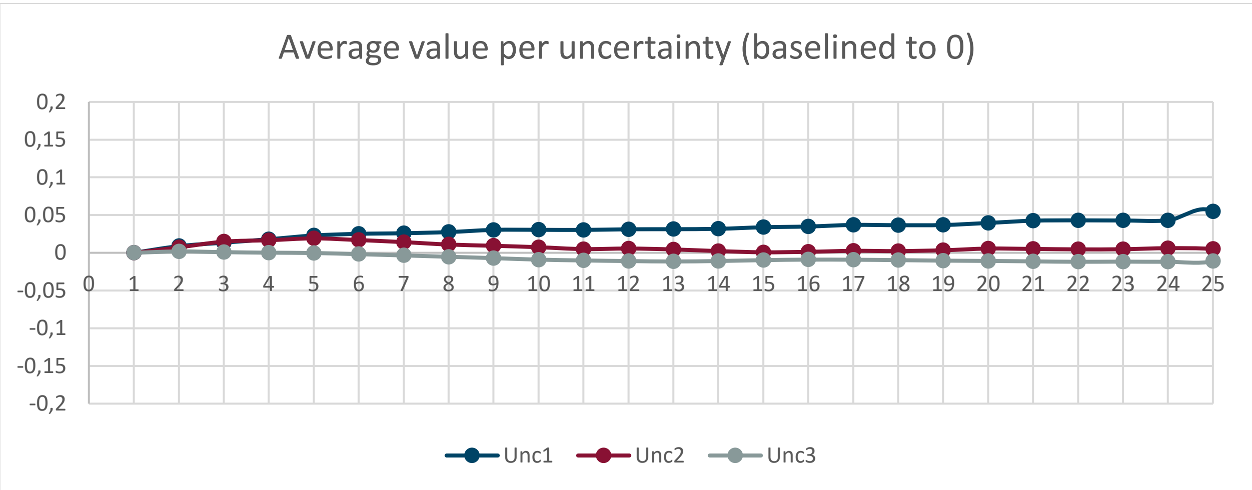

Figure 4. The difference in arousal across different types of uncertainties.

Subsequently, in figure 4 we see that the 1st uncertainty caused higher arousal than the other two. Then, we divided the factor score of arousal back into 3 separate dependent variables. In the table below we present the results of three different linear regression analyses, namely with the arousals of the 1st, 2nd, and 3rd uncertainties as dependent variables.

The results show that actually, uncertainty communication only leads to higher arousal in the 1st type of uncertainty, which is the remaining radioactivity. It has no significant effect on the other 2 types of uncertainties. Familiarity with decommissioning and uncertainty intolerance do not have a significant effect on the arousal related to any of these uncertainties. However, when we created an interaction term of uncertainty intolerance with the experimental group in order to see the moderation effect that uncertainty intolerance can have on the effect of uncertainty communication on participation intention, we obtained an interesting negative effect. This means that the effect of uncertainty communication on arousal decreases as intolerance for uncertainty increases which is contrary to what we expected. A potential explanation for this could be that given that most of our participants are aware that decommissioning is associated with uncertainties, those that have high uncertainty intolerance have higher arousal when they receive only introduction to decommissioning, without any additional information on uncertainties (when they know such uncertainties exist). For a robustness check, we also conducted analyses without the interaction term and the effects were not that different to the ones presented in the table below.

Table 4. Logistic regression results with arousals of 3 types of uncertainties as dependent variables.

	Arousal: Unc1: Remaining radioactivity	**Arousal: Unc2: Radioactive waste**	**Arousal: Unc3: Financial costs**
Explanatory variable	Estimate	Estimate	Estimate
Experimental group	**.057***	.048	.049
Familiarity with decommissioning	.024	.020	.026
Uncertainty intolerance (UI)	.021	.022	.021
Interaction term: UI x Exp.group	**-.075****	**-.059***	**-.130*****
	N= 134 R^2= .10	N= 134 R^2= .07	N= 134 R^2= .15

*$p < 0.05$; **$p < 0.01$; ***$p<0.001$

Discussion

In this study we conducted an experiment using a survey and psychophysiological measurement of emotional arousal in order to test 1) whether communicating uncertainty influences participation intention directly, and 2) whether this impact is mediated by emotional arousal. Theoretically, this study is mainly based on the Uncertainty Reduction Theory (URT) and Uncertainty Management Theory (UMT) based on which we formed several hypotheses and tested them by regression analyses and structural equations modelling.

Based on URT, we hypothesized that (H1) participants that received uncertainty communication (experimental group), would be more likely to participate in decision-making procedures. However, contrary to this hypothesis, results of this study showed that uncertainty communication does not have a significant effect on participation intention. In line with this theory, we also hypothesized that (H1a) people who have higher intolerance for uncertainty are more likely to participate as they need to gain more information by participating in the process. This effect seemed to be indeed significant indicating that participants who could not handle uncertainties, were more likely to participate in decision-making procedures.

Then, based on UMT, we hypothesized that (H2) the effect of uncertainty communication on participation intention is mediated by emotions, which we measured by psychophysiological measurement of arousal, and (H2a) self-reported feelings. We found that uncertainty communication does not influence self-reported feelings but it indeed has a significant effect on emotional arousal. Neither of these variables influence participation intention, though. This lack of effect can still be explained by UMT. UMT argues that if uncertainty communication causes negative feelings such as worry or anger, it can lead to higher participation intention. However, given that in our study, participants that received uncertainty communication did not report any negative or positive feeling, and hence, there is no linkage with participation intention. The impact of uncertainty communication on emotional arousal appears not to be strong enough either, to induce participation intention.

In order to dig deeper into the exact nature of the impact of uncertainty communication on emotional arousal, we conducted 3 separate regression analyses for each type of uncertainty. We found that uncertainty communication in fact influences only the arousal towards the 1st type of uncertainty which states that "experts are uncertain if the amount of remaining radioactivity will be accepted by the public". This is an interesting finding as it shows that our participants reacted more towards the uncertainty of the acceptance of remaining radioactivity by the public, than other types of uncertainty like radioactive waste or financial costs of decommissioning. In a scoping review which analyzed the uncertainties of various actors, Hoti, Perko, Thijssen, & Renn (2020) found that the literature focusing on the uncertainties of experts mainly mentioned technical or methodological uncertainties. Therefore, saying that experts are uncertain about how the public will react about remaining radioactivity could be a type of uncertainty that our participants have not been used to be mentioned. Another potential explanation is that our participants already knew this type of uncertainty but did not see it as the most important one to be mentioned or they were reminded of a type of uncertainty they would like to forget.

Concerning participation intention, we also found that variables that have a direct influence in it are attitude towards participation, moral norm, and time constraints, and we therefore confirm hypotheses H5, H6, and H7, which were supported by items of Theory of Planned Behavior (Ajzen, 1991).

Familiarity with decommissioning had an indirect effect on participation intention, which indicates that participants that are more familiar with the topic of decommissioning had more positive attitudes towards participation and were therefore more likely to participate. This is supported by existing literature on public engagement in activism (Sabherwal et al., 2021), albeit in our study we did not find a direct effect, but rather an indirect one through attitude towards participation.

This study contributes to research on uncertainty communication by being the first one to addressing two different research gaps. First, it contributes to research on participation intention by analyzing the impact that uncertainty communication can have on it, and second, it is the first one that analyzed the impact that uncertainty communication can have on emotional arousal by means of psychophysiological measurement. Given that there is very little (and contradictory) research on the impact of uncertainty communication on emotions, and even those that exist are rather theoretical in nature, the empirical character of this study and the inclusion of psychophysiological measurement contributes to further advance the discussion of the impact of uncertainty communication on emotions. However, this study also has some limitations. For instance, uncertainties that were shown to participants, were shown in the same order and not randomly. This could lead to order effect in the results of uncertainty communication on emotional arousal. Therefore, we recommend future research to change the order of different types of uncertainties in order to see if the results are affected by the order or not. Furthermore, while convincing experts of the nuclear field and other employees that work in a nuclear-related facility to participate in a study where their psychophysiological measurements would be taken, albeit very challenging, allowed us to acquire useful and interesting results. However, while these findings provide clear contribution in the uncertainty communication debate, one major drawback is that no inference with the general public or other groups is possible. For this reason, we recommend future research to analyze these aspects with participants from the general public so that comparisons can be made.

Conclusion

Decommissioning of nuclear installations is a multidisciplinary set of processes, which are long, expensive and complex and by which many uncertainties about the future are generated. For this reason, it is recommended that the public should be involved in decision-making procedures related to decommissioning (Hoti et al., 2021) and also that uncertainties should be admitted and communicated (Perko, Monken-Fernandes, Martell, Zeleznik, & O'Sullivan, 2019). However, there is very little research on the effects that uncertainty communication can have on various factors such as emotions and participation intention. Even those articles that paid attention to the effects, have contradictory findings (Han, 2012; Jensen, 2008; Knoblauch et al., 2018; Maxim et al., 2013; T. Perko, Benighaus, Tomkiv, & Wolf, 2020) and are either theoretical in nature or have only used self-reported measurement of feelings, without a single study adding the psychophysiological measurement to test these effects.

In order to build on this, in our study we conducted an experiment with employees of the Belgian Nuclear Research Centre (SCK CEN), Belgoprocess and VITO (experts that are expected to be more familiar with decommissioning than the general population) by using a survey and psychophysiological measurement of emotions in order to test 1) whether communicating uncertainty influences participation intention directly, and 2) whether this impact is mediated by emotional arousal. Theoretically, this study is mainly based on the Uncertainty Reduction Theory (URT) and Uncertainty Management Theory (UMT) and we used regression analyses and structural equations modelling as analysis.

We found that participation intention is influenced by attitudes towards participation, moral norm and time constraints directly. This is not surprising but we provided statistical evidence for this effect as well as its strength. Familiarity on the topic influences participation intention indirectly, through attitude towards participation. However, uncertainty communication, our main variable of interest, does not influence participation intention. This variable does influence, though, emotional arousal, more specifically, emotional reaction towards uncertainties concerning the public acceptance of the remaining radioactivity resulting from decommissioning.

Regarding self-expressed feelings, the findings of the study suggest that uncertainty communication does not generate negative feelings such as anger or fear. Given that there has been a debate on whether or not uncertainties should be communicated, the findings of this study mean that there is no reason why uncertainties should not be communicated as they do not cause negative feelings (based on participants' self-expression of emotions). As per emotional arousal, it only increased arousal concerning the 1st type of uncertainty, which we have not been used to see being mentioned in the literature so far.

The findings of this study contribute to research on uncertainty communication by addressing two main research gaps, namely, it contributes to the lack of research on the impact of uncertainty communication on public participation intention, and second, on the impact that uncertainty communication can have on emotional arousal by means of psychophysiological measurement. However, given the background of our participants, the findings of this study cannot be generalized for the general or other types of population.

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Disclosure

The author reports that there are no competing interests to declare.

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Chapter 7: Discussion and Conclusion

The goal of this dissertation was to study uncertainties that are present in nuclear and/or radiological risk situations, and the impacts that communication of such uncertainties has on emotions and participation intention of both, experts, and laypeople. In this section I present a self-critical discussion of the main findings in the previous chapters. This discussion will be structured along the three main research questions in the objectives of the thesis, namely, 1) what types of uncertainties are there in radiological risk situations?; 2) what is the impact of uncertainty communication on participation intention?; and 3) what is the impact of uncertainty communication on emotions. Afterwards I will discuss theoretical and practical implications of the findings, as well as some of the limitations and recommendations for future research.

What types of uncertainties are there in nuclear and/or radiological risk situations?

To explore the existing types and definitions of uncertainty in nuclear and/or radiological situations, together with my co-authors, I first conducted a scoping review in order to identify types and definitions of uncertainty in literature. Afterwards, I conducted non-participatory observation of nuclear and/or radiological emergency exercises in order to identify different uncertainties present in practice, more specifically in nuclear/radiological emergency scenarios.

The scoping review (chapter 2) was the most appropriate method to use since it allowed for mapping and bringing together the existing literature present in different study areas evolving around a broader research question with scattered evidence (Tricco et al., 2016). In so doing, it contributes to literature in the nuclear/radiological field by not only identifying the uncertainties that appear in this field, but also comparing them to other research areas as well as finding understudied topics that need further research attention (e.g. decommissioning of nuclear installations).

The findings showed that there are many definitions and types of uncertainty present in the literature related to nuclear/radiological risk situations. Definitions of uncertainty were different in the sense that some of them defined uncertainty as purely knowledge-related (Walker et al., 2003), whereas others included also the aspect of perception and emotion (Han et al., 2010; Maxim, 2014; Morris-Suzuki, 2014). While lack of consensus concerning definition of a specific term is not uncommon, and given that it is rather difficult to use a single definition of uncertainty considering the big differences of disciplines in which uncertainty is present, in this thesis I argue that communication of uncertainties should be accompanied by a clear description of what is meant with the concept of uncertainty. Types of uncertainties present in the literature ranged from epistemic (knowledge-based, related to the unknowns); aleatory (uncertainties of stochastic, random nature); ambiguity (different interpretations of a wording or situation); decision (different decisions made based on different interpretations of the information); communication (how complete and understandable a certain information is); technical (e.g. technical errors due to imprecise instruments or methods); methodological (due to methodological challenges); and pragmatic uncertainties (uncertainties resulting from the difficulties encountered in policy-making processes) (Doyle et al., 2014; Knoblauch et al., 2018; Maxim, 2014).

From the scoping review, I also learned that different actors are faced with different uncertainties. What can be an uncertainty for a scientist (e.g. theories of low-dose radiation), can be a cause of uncertainty for decision-makers (e.g. what to take into account in risk assessment and decision-making), and as a consequence, it can result in worry or concerns amongst the laypeople. While the majority of the literature is focused on the uncertainties of the scientific community, those of decision-makers and laypeople (i.e. information receivers) are analyzed to a much lower extent. This shows that research is mainly focused on the top-down communication process (information issued by scientists to other actors) when studying uncertainty communication and decision-making under it.

This is particularly an issue given that based on our findings, uncertainties of the scientists are more technical and methodology-driven, those of decision-makers are more related to the potential consequences of the decisions made, while the uncertainties of the laypeople are more related to issues such as trustworthiness of experts or the emotional potential of special risk exposure. When attention is only paid to top-down communication, the risk of not addressing communication needs of the information receivers appears. Only when we understand the uncertainties of the different actors, can we address them through communication practices and contribute to better decision-making. This is why in the third chapter, together with several colleagues from various EU countries, I observed nuclear/radiological emergency exercises, in order to see which actors are faced with which uncertainties in such situations.

Nuclear and/or radiological emergencies are one of the case studies of this thesis. During such emergencies, all the affected actors (e.g. citizens, decision-makers, and experts) need to make decisions under high uncertainties. This makes this case study an optimal one to observe and identify the occurring uncertainties. By using non-participatory observation of nuclear/radiological emergency exercises, this chapter contributes to literature on uncertainties in nuclear/radiological emergencies as it offers results that are studied in highly realistic scenarios. The uncertainties identified in this chapter were grouped based on the types of uncertainties as identified in the second chapter (i.e. epistemic, aleatory, ambiguity, communication, etcetera). Furthermore, they were also grouped in different decision-making procedures based on the adapted conceptual framework proposed by Sorensen and Mileti (1987), Groβe (2019), and Afifi and Weiner (2004) in five stages of decision-making process. These stages are: 1) the *knowledge* stage (where uncertainties that may appear are related to lack of-, incomplete or insufficient knowledge/information); 2) the *judgement* stage (actors may be unsure about the consequences of different decision options); 3) the *decision* phase (actors may be unsure about how to make a decision given the available options and their advantages and disadvantages); 4) the *implementation* stage (uncertainties are related to practical implementation of the decisions that were made and the expectations of what impacts the implementation of management measure may have); and 5) the *evaluation/monitoring* stage (where uncertainties may appear when there is discrepancy between expectations and observed results and the reasons for this discrepancy are either unknown or contested).

The findings of the 3rd chapter show that all types of uncertainties (i.e. epistemic, aleatory, ambiguity, pragmatic, technical, communication and others) appear in the behavior, decision-making of-, or during the communication flow among participants as observed during nuclear/radiological emergency exercises. However, similar to previous studies (Hoti et al., 2020; Maxim, 2014; Walker et al., 2010), I found that it is difficult to categorize the identified uncertainties into single types as there can be strong interrelation between these different types. I therefore clustered these uncertainties into 32 thematic groups of uncertainties, and then linked them with the different decision-making procedures. A recurring observation in this chapter was that while different actors where faced with different uncertainties, they influenced one another. For instance, biased or incorrect information is transported in the next chain in the communication sequence and this amplifies the uncertainties of other actors. Furthermore, waiting for more accurate results before issuing public information, resulted in uncertainties for the potentially affected population. This points to the importance of timely and transparent communication, even if it involves uncertainties. Finally, I also found that, when it comes to decision-making stages, most uncertainties that resulted from our observations are related to the practical implementation of actions, e.g. the potential for unexpected failure of communication, or the inadequacy of the written plans to cope with the real situation. This indicates that to prevent or to mitigate uncertainties in the implementation stage, additional steps need to be made to strengthen emergency management, and to improve communication and collaboration between different actors in emergency situations. Some of these steps include working closely with involved actors including the affected population and those most impacted by the situation at hand. This would make it easier to realize what kind of information needs to be communicated to reduce uncertainties and allow the affected population make informed decisions.

To sum, the findings of the chapters 2 & 3 suggest that there are different types of uncertainties that various actors are faced with when it comes to nuclear/radiological risks. However, based on our results, most research is focusing on the uncertainties of the scientists or experts, while information about the receivers' side and their reaction to uncertainty communication is understudied. In addition to this, there is no research studying uncertainties and their communication in the case of decommissioning of nuclear installations. This is why, to accomplish the 2nd and the 3rd objectives of this thesis, in the next three studies (chapter 4, 5, and 6), I focused on public participation in decision-making procedures related to decommissioning of nuclear installations, as the main dependent variable when testing how different actors (i.e. experts vs. public) react to uncertainty communication. The reason why I test for both, experts, and laypeople is because according to research in risk perception and communication in the nuclear and radiological field, experts perceive lower radiological risks than laypeople because of their familiarity with the issue (Perko, 2014). Based on this, I hypothesized that the results will be similar with respect to uncertainties. More specifically, I expected that experts are least likely to have a strong emotional reaction towards uncertainty communication given they face uncertainties on a regular basis, and they are more willing to participate in decision-making procedures about decommissioning of nuclear installations, given their familiarity with the topic. Contrary to this, I expected that laypeople are a most-likely case for finding a reaction towards uncertainty communication, given that uncertainty is very often excluded from communication to the public (Harris, 2015; Jensen et al., 2011), and the more uninformed they feel about decommissioning, the less likely they are to be willing to participate.

In the next sections I summarize the findings of these three studies and answer the main research questions as part of the 2nd and 3rd objective of the thesis.

What is the impact of uncertainty communication on participation intention?

From the first chapters of this thesis, it became clear that uncertainties are an inherent part of risk management, and they affect different parts of the population to various extents. This points to the importance of integrating the knowledge, expertise, values, interests, and concerns of different stakeholders in the decision-making process (Bergmans et al., 2015; Bond et al., 2004; Hage & Leroy, 2008; Pellizzoni, 2003; Renn, 2015). Furthermore, I also found that the majority of research is focused on top-down communication and the impacts of it. Yet, because of the importance of multi-way communication, and the integration of different forms of knowledge, public participation in decision-making procedures is considered a crucial element of risk communication (National Academy of Sciences, 2013; Renn, 2008). It gives citizens the opportunity of learning about the technical and political facets of decision-making options and enabling them to discuss and evaluate these options and their likely consequences according to their own set of values and preferences (Renn, 2008). However, until the start of this dissertation, it was not known to what extent different actors (experts and laypeople) are willing to participate in decision-making procedures related decommissioning of nuclear installations. Because this topic appeared to be an understudied one based on our scoping review, and because it is a highly relevant topic at the time of writing this thesis, in order to test participation intention, I used decommissioning of nuclear installations as the second case study of this thesis.

To address the second objective, I first used data from a public opinion survey conducted in 2015 with a representative sample of the Belgian population (N=1028), in order to first identify to what extent members of the Belgian population are willing to participate in decision-making procedures related to decommissioning of nuclear installations (chapter 4). After analyzing the public intention to participate in such decision-making procedures, as well as the factors that influence this willingness, I proceeded to add uncertainty communication as the main independent variable, in order to see if this variable influences participation intention. To do this, I conducted two survey-embedded experiments, one with the general population (chapter 5, N=1060), and another one with employees of nuclear-related institutions (chapter 6, N=133). Surveys proved to be the most appropriate method for testing these hypothesized effects among larger samples, which allowed for greater statistical power in validating the hypothesized models.

Findings of these studies show that, if we exclude protests or activism (which were not the specific goal of this dissertation), a major part of the public in general does not intend to actively participate in organized decision-making procedures. In 2015, 18% of our survey participants were willing to receive information and express their opinion about decommissioning, whereas only 8% of them were willing to be actively engaged in decision-making procedures concerning decommissioning of nuclear installations (e.g. engage in discussions with other actors). In comparison to previous years, though, in 2021 there appears to be a progress on public's intention to participate, with 32% of the participants willing to receive information and express their opinion, and 13% willing to be involved in more active forms (Hoti, Perko, & Turcanu, 2021). However, I also found that there is a difference between intended versus actual participation. When I presented participants with a "real" opportunity to participate in a decision-making procedure about decommissioning of nuclear installations, their willingness to participate was much lower than in a hypothetical scenario. This means that intention to participate is not a given and that a crucial element is participation intention is still rather low, even when people are given the opportunity to participate. This is why it is important to continue testing ways to increase public participation intention, as well as ways that ensure that these participation procedures are balanced and equal both, in the recruitment, as well as in the participating/decision-making procedures.

When testing which factors influence participation intention, I found that communication of uncertainties did not influence it neither directly, nor indirectly. Nevertheless, when asked if they would like to receive information about decommissioning that involves uncertainty, the majority of participants (62%) said that they would like to receive such information (Hoti, Perko, & Turcanu, 2021). This points to the importance of including uncertainty in scientific communication since although it might not necessarily trigger information receivers to be engaged in decision-making procedures, they still expect and want to receive information about the existing uncertainties.

To sum, results show that when it comes to public participation, the causal relationship is much more complicated than simply A leading to B. Rather, there is a whole set of inter-related variables that are influencing this relationship. For instance, I found that several factors such as attitude towards participation, risk perception, perceived level of information and interest on the topic have an effect on participation intention. Other factors leading to higher participation intention were low trust in the nuclear industry, being ideologically leftist, having more negative attitudes towards nuclear energy, familiarity with the topic of decommissioning, and living in the vicinity of a nuclear installation influences participation intention too. This shows that while public participation in decision-making procedures is a crucial process to ensure inclusive, transparent, and more legitimate decisions, more attention needs to be paid in ensuring unbiased participation. Given that I found that mainly people that are already familiar and interested on the topic of decommissioning are more willing to participate, we need to make sure that various opinions and points of view are represented in such procedures in order for it to be fair, balanced, and to ensure trust in similar procedures in the future.

What is the impact of uncertainty communication on feelings and emotional arousal?

In the section above I pointed to the relevance of transparent and informed decision-making procedures. One crucial element contributing to such transparency and informed decisions, is communication of uncertainties (Hoffman et al., 2011; SHARE, 2020). Decommissioning of nuclear installations is a process which involves many uncertainties, and this is why the International Atomic Energy Agency (IAEA) has produced guidelines on how to address such uncertainties, mainly focusing on improving estimates (IAEA, 2017). However, testing the impact of uncertainty communication on the receivers of the information is not included in these guidelines. Uncertainty communication has recently been tested in various research areas though (e.g. medicine, natural hazards, food safety) (Doyle et al., 2014; Hart et al., 2019; Knoblauch et al., 2018; Maxim et al., 2013). The findings regarding its impact on feelings and emotions, however, remain contradictory. On the one hand, some studies found that uncertainty communication causes negative feelings (e.g. fear and anger) (Han et al., 2010; Knoblauch et al., 2018), whereas others found that communication of uncertainties actually reduces negative feelings (e.g. worry, fear, proneness to backlash) (Jensen et al., 2016; Jensen, 2008; Maxim et al., 2013). Still, the majority of these arguments are either theoretical in nature, or have only been tested with self-reporting items.

In an attempt to contribute in solving this debate, as well as to address this research gap in the nuclear/radiological field, in this thesis I conducted two survey-embedded experiments, one with the general population (chapter 5, N=1060), and another one with employees of nuclear installations, divided into experts versus non-experts (chapter 6, N=133). The latter study involved psychophysiological measurement of emotional arousal as a mediator to the hypothesized effect of uncertainty communication on participation intention in order to have a deeper understanding of the emotional effect. Using these methods in two different samples allowed for comparison between participants that are familiar and/or experts with decommissioning, and those that are not. Furthermore it allows for testing the differences in the emotional effect of uncertainty communication among these participants.

Findings of these two studies showed that communication of uncertainties had different effects among different samples. When studied with the general population, communication of two out of three uncertainties (the amount of radioactive waste, and financial uncertainties) slightly negatively influenced self-assessed feelings of pessimism and worry. When tested with employees of nuclear-related institutions, though, uncertainty communication had no significant effect on self-assessed feelings. Nevertheless, the psychophysiological measurement showed a significant increase in participants’ emotional arousal when uncertainty about “public’s acceptance of remaining radioactivity” was communicated. This shows that different groups of the society not only have different reactions to uncertainty communication, but they also react to different uncertainties. Other variables such as gender, education, risk perception and familiarity with decommissioning also influenced feelings and emotional arousal. Removing certain groups from the analysis (e.g. lower education or respondents with a higher risk perception) would significantly change the results. This shows the importance of analyzing and paying attention to different groups of the society and not treating it as a whole or a single group.

To sum, uncertainty communication slightly influenced negative self-assessed feelings among participants in the survey with the “general” population. When tested with experts, it did not influence self-assessed feelings, but the uncertainty about public reactions of remaining radioactivity significantly increased their emotional arousal. However, there is no correlation of this emotional arousal with the self-assessed feelings (anger and worry) that I measured. This means that this emotional arousal can be linked to- or explained by another type of feeling or emotion that I did not measure in this study. It further shows the importance of including the psychophysiological measurement of emotional arousal as an additional measurement. Without this measurement, we would have simply concluded that uncertainty communication does not influence self-assessed feelings. However, the psychophysiological measurement offers results which point to some deeper effects that future research should pay more attention to.

In the next section I explain what the practical and theoretical implications of these findings are.

Practical implications and recommendations

The nuclear/radiological field is a very interesting domain to be studied when it comes to uncertainties and their communication given the complex nature of such high risk, high gain technology, which involves many uncertainties, and where decisions have to be made carefully given that they can have a major impact on people's lives, health, and the environment, even from an inter-generational perspective (IAEA, 2011; Taebi, 2012). The findings of this thesis thus not only add to the missing literature on the impacts of uncertainty communication in this field, but they also provide practical recommendations for both, nuclear/radiological emergency situations, as well as for the upcoming decommissioning projects in Belgium and other democratic countries.

To explain the implications of the results concerning uncertainty communication in the nuclear/radiological field, I would like to restate the main objective and rationale behind uncertainty communication, which is to contribute to informed decision-making amongst the receivers of the information (Doyle et al., 2014; Patt & Weber, 2014). Thus, based on the findings, I recommend that when communicating about uncertainties, we need to acknowledge the fact that uncertainties diverge (and potentially broaden) from scientists to decision-makers and finally to the laypeople. We need to make to make sure that information providers speak the language of the information receivers, in providing them with all the information they would like and need to have.

Our findings showed that while uncertainty communication did not influence participation intention, it did slightly influence negative feelings of worry and pessimism. But this does not mean that we should refrain from communicating uncertainties. On the contrary, I argue that while uncertainty might indeed cause some emotional effect on the short term, long term uncertainty information and familiarity with uncertainties will give assurance and comfortability with uncertainty information. This argument is supported by the findings of the 6th chapter of this thesis where I found that uncertainty communication does not cause negative feelings among people that are more familiar with uncertain results and processes, as well as are encountered with uncertainties in the nuclear field on a more frequent basis. This means that if we continuously include information about the existing uncertainties, people will start to feel more comfortable with it. At the end, I found that this is actually what they want. More specifically, I found that the majority of the respondents (62%) would like to receive information about decommissioning even if it contains uncertainties. If such important information is withheld from the public, and they are later communicated by someone else (e.g. a non-governmental organization) it can lead to a decline of trust and reputation in the communicators and involved authorities. So even if uncertainty information may increase confusion or negative feelings among the information receivers, it is nevertheless essential to sustain a trusting relationship between the communicators and their respective audiences.

In this thesis I argue that in order for the decisions in the nuclear/radiological field to be made in an informed and effective way, communication and exchange of ideas, experience, and expertise of various actors is needed. This would help in offering different perspectives, create mutual understanding, build trust among various actors, and make decisions more legitimate. One way to ensure this multi way communication is public participation in decision-making procedures. When testing to what extent different actors (experts versus public) are willing to participate in decision-making about decommissioning of nuclear installations in Belgium, and what factors influence this willingness, I found that it depends on many factors. Mainly, people that are already more easily recruited, namely participants that are more negative about the potential decisions, that are more interested on the topic, that have more time to participate, have more positive attitudes towards participation, and are more familiar with the topic, are more likely to participate. This points towards the risk of bias in participation. This is why I recommend that in decision-making procedures, we need to make sure that all diverse opinions are represented in order for the discussion to be fair and comprehensive. Some ways to ensure this are organizing regular public opinion follow-up (given the changes in public opinion due to various triggering events), stakeholder identification and analysis to make sure that under-represented groups are also a part of the process, as well as active conflict management and inclusion of mediators to make sure that opinions and visions are properly interpreted and translated into results. Providing debriefing and reporting to the participants afterwards is also recommended, in order to show them to what extent their contribution has been taken into account in the final decision. These findings apply not only to decommissioning of nuclear installations, but also to broader participatory and/or stakeholder engagement efforts.

While I found that intention to participate is rather low, we also know that in practice, we cannot recruit everyone in the participatory procedures. The goal should thus be to ensure that these participation procedures are balanced and equal both, in the recruitment, as well as in the participating/decision-making procedures. Such participatory procedures are considered to be fair if they empower the participants to not only give their opinion, but to also have an influence on the decisions made. This is why it is of crucial importance to provide debriefings and report to the participants on how their comments and their contributions have influenced the final decision. This benefits not only the affected stakeholders, but also the decommissioning program and the society at large.

Some of the findings of this dissertation have already turned into practical contributions. For instance, in the nuclear/radiological emergency exercises, I observed that one of the occurring uncertainties was related to "whom to follow during such emergencies/what is the hierarchy in this situation?". After our report, there are vests foreseen for the commanders where it is clearly written that they are the commanders, and their recommendations need to be followed.

Theoretical implications, limitations, and recommendations for future research

From the theoretical standpoint, given its case selection, this dissertation, is primarily inspired by the Post-Normal Science (PNS) paradigm, which is an approach for the use of science on issues where "facts [are] uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz & Ravetz, 1997: 169). From the PNS paradigm, uncertainty communication and stakeholder and public involvement go hand-in-hand (Petersen et al., 2011). At the same time, from existing literature we know that the more uncertainty there is, the more public participation is needed (Renn, 2015). Yet, up till the start of this dissertation, the relationship between these two variables - uncertainty communication and participation - has not been empirically tested. The findings of the dissertation showed that communication of uncertainties does not influence participation intention neither among the general public, nor among experts. Albeit the results showed a null effect concerning this relationship, this dissertation still makes an important theoretical contribution to the PNS paradigm by testing the relationship between two of its most important focus points.

While the PNS paradigm was the overarching framework of this dissertation, in order to form the hypotheses of the separate chapters, I adapted and synthesized concepts and theoretical models stemming from a number of fields such as: Uncertainty Reduction Theory (URT) (Berger, 1986; Bradac, 2001), Uncertainty Management Theory (UMT) (Brashers, 2001)); Cognitive Functional Model (CFM) (Nabi, 1999), Affective Intelligence Theory (AIT) (Marcus et al., 2002); Value-Belief-Norm Theory (VBN) (Stern et al., 1999) and Arnstein's ladder of participation (Arnstein, 1969).

Literature that studied the impacts of uncertainty communication has mainly used the arguments of the URT or UMT. The URT mainly argues that people are most of the time willing to reduce uncertainty by seeking more information (Bradac, 2001), whereas UMT argues that actually this depends on how uncertainty makes them feel. If uncertainty is seen as a threat, people are willing to reduce it. On the other hand, if people see uncertainty as an opportunity, they are less likely to react on it (Brashers, 2001). Testing of these theories has mainly been made by focusing on information-seeking behavior of study participants. This dissertation advances the testing of these theories by testing them not only on information-seeking behaviors of respondents, but also their intentions to express their opinions and actively contribute to participatory procedures.

While the theoretical arguments about whether or not to communicate uncertainties mainly rely on its impacts on feelings and emotions, this causal relationship has not been sufficiently tested either. In this dissertation I have used arguments of the CFM and AIT to test the impact of uncertainty communication on these two variables. CFM argues that feelings such as anger are more likely to make participants want to approach or engage with the message and the source of the feeling, regardless whether their expectation of information reassurance is certain or uncertain (Nabi, 2002). On the other hand, participants that experience emotions such as fear or worry will refrain from engaging because fear makes individuals 'shrink from action' and cause lack of control (Karl, 2021: 693). However, if there is uncertainty about the fear or worry-inducing message, and the person facing these feelings believes that getting more information and/or being engaged in a decision-making procedure will bring additional information to satisfy/address their emotions, then motivation to engage with the affect's source is increased (Nabi, 1999, 2002). Similarly, AIT argues that people have two separate emotional systems leading to two different decision-making strategies: the disposition system (involving feelings like enthusiasm and aversion, which leads people to rely on existing habits), and the surveillance system (involving feelings like anxiety and thus leads people to seek more information and participate in decision-making procedures) (Marcus et al., 2002; Vasilopoulos, 2019).

While the impact of uncertainty communication on feelings and emotions has mainly been tested with self-assessed scale, this dissertation advances this hypothesis testing by adding the element of psycho-physiological measurement of emotional arousal. The findings of the dissertation show that one type of uncertainty communication slightly influenced participants' emotional arousal, when measured among participants that work in nuclear-related institutions. Uncertainty communication also influenced self-assessed negative feelings among the general population. In none of these studies, however, the feelings and emotional arousal generated by uncertainty communication, did not influence participants' participation intention. These findings contribute to the CFM and AIT theories by not only testing them in the nuclear field, a field where this relationship has not been tested before, but also by testing these theories with the psychophysiological measurement of emotional arousal.

Finally, when it comes to participation intention, in this dissertation I also used the VBN theory and the Arnstein's ladder of participation. To the best of my knowledge, this dissertation uses both, the VBN theory, and the Arnstein's ladder of participation for the first time in the topic of decommissioning of nuclear installations. The results confirm the arguments of the VBN theory by finding that public participation intention about decommissioning is indirectly influenced by variables such as trust, vicinity, altruistic and biospheric values, as well as attitudes towards nuclear energy on participation. However, this effect is not direct, but rather mediated by variables such as risk perception and interest on the topic. This contributes on literature on public participation intention by finding that focusing on a single theoretical framework is not sufficient to predict participation intention, given that the causal relationships are much more complicated and depend on a variety of predictors. This is why in the next chapters of the dissertation I used a combination of various theories to test the hypotheses and to contribute to literature by testing for the first time what influences participation intention about nuclear decommissioning. Furthermore, I have used the Arnstein's ladder of participation not only on a hypothetical scenario, but by also giving participants a realistic scenario to test their intention to participate in decision-making procedures. This contributes to literature on participation intention in nuclear decommissioning by providing a more realistic view of to what extent the Belgian population is willing to participate in such decision-making procedures, and what factors influence such willingness. Given that based on the findings of chapter 3, as well as based on the existing literature, the types of uncertainties seem to be similar across different countries, this makes the findings generalizable for the other democratic countries too.

What about the generalizability with the other research fields? The findings of the second chapter of this dissertation showed that the types of uncertainties present across different research areas (nuclear versus others such as natural hazards, medical field, etcetera) are relatively similar and that the main difference is across actors rather than across research fields. This makes the findings of this thesis generalizable to other fields as well. But if types of uncertainties are similar in various fields, then what makes the findings of this thesis distinctive? The findings of this thesis add to missing and/or understudied parts of the uncertainty aspect.

First, while previous studies have tested different formats (e.g. verbal, numerical, visual communication) of uncertainty communication, in this thesis I tested different types (public acceptance of remaining radioactivity, the amount of radioactive waste, and the financial uncertainties of decommissioning a nuclear installation) of uncertainty communication. Given that the nuclear decommissioning field is an understudied one when it comes to uncertainty communication, testing different types of uncertainties was a useful way to understand what aspects are more important for different audiences of uncertainty information receivers. *Second*, with the help of this theory combination, I was able to test for the first time whether uncertainty communication directly or indirectly influences participation intention in decision-making procedures. This causal relationship is a crucial one to study given that both, uncertainty communication and public participation in decision making procedures are currently pertinent issues in the nuclear decommissioning field. Understanding the impacts of uncertainty communication, and what influences participation intention, is a relevant addition to the missing literature in the social aspects of decommissioning of nuclear installations. *Finally*, using feelings and emotions as mediating variables, allowed for better understanding of the affective reaction of uncertainty communication, contributing to the theoretical debate on the impact of uncertainty communication on feelings and emotions. This has a significant contribution not only to the contradictory arguments in the literature, but also to the research need for testing the impacts and handling of uncertainty communication among different target audiences.

This thesis has its limitations and its own uncertainties that need to be communicated too. For instance, in the scoping review, due to a specific set of keywords that this dissertation was focused on, I ended up with a limited set of articles to be analyzed. The observation of nuclear/radiological emergency exercises allowed us to observe more uncertainties in realistic scenarios, but this study had some limitations too. Because of selection of specific observation points, I was disproportionally focused on certain actors such as emergency managers and first responders than on the affected population. This caused us to identify more uncertainties on the former actors than on the latter. I would therefore recommend future research to focus more on the uncertainties of the affected population and/or the general public.

While testing the potential impact of uncertainty communication on feelings and emotional arousal has its contributions, there are also some limitations to these studies. First, when testing uncertainty communication, I framed uncertainties as "uncertainties that experts are faced with", which based on previous research are found to cause more negative feelings than uncertainties that are framed as "error ranges and probabilities" (technical uncertainties) (Gustafson & Rice, 2020: 614). This is why I would recommend that future research tests different ways of uncertainty communication, and different framings of uncertainties.

When testing uncertainty communication with the psychophysiological experiment, uncertainties were displayed to participants in the same order, and not randomly. This is an additional limitation of this thesis as it could lead to an order effect bias in the results. I therefore recommend future research to change the sequence of different types of uncertainties so that one can see if the results are affected by this sequence or not. Furthermore, because this experiment was conducted with a specific non-representative sample, it does not allow for generalizations among the general population concerning the psychophysiological effect. Hence, I recommend that future studies measure the psychophysiological effect of uncertainties also with the general population.

This research design and data collection of this dissertation has been significantly influenced by the Covid-19 pandemic. Initially, the goal was that the psychophysiological study would be also conducted with a representative sample of the general population, in order to have a proper comparison among different audiences in terms of emotional arousal too. However, due to Covid-19, it was impossible to have face-to-face interviews, and put the same device on multiple people's hands. Furthermore, the public opinion survey was also planned to be face-to-face, but was instead conducted online due to the pandemic.

A more general limitation is that while I tried to combine top-down (experts uncertainties) with bottom-up (public participation in decision-procedures) communication approaches, I still tested uncertainty communication from experts to information receivers such as general public or participants that are more familiar with the decommissioning issues. It would be of great importance that future studies also test how communicating public's uncertainties would influence reactions of experts and decision-makers.

It is important to also state that while the results of the models in this thesis had very good fits, there is still a significant unexplained variance, which points that both, uncertainty communication and participation intention are more complicated than we expect. We are still far away from having ultimate answers on the impacts of uncertainty communication, and knowing how to increase public participation intention.

Key messages

Despite the limitations of the studies of this thesis, there is still a set of key messages that can be drawn from its findings:

- Uncertainty communication is a crucial element for transparent and informed decision-making. Uncertainties must therefore be admitted and clearly communicated. While in the short term there might be some negative emotional reaction, long term uncertainty communication will ensure trust in- and comfortability with the uncertainties and the decisions that need to be made.

- Uncertainties and perceptions of the information receivers (in addition to those of information providers) need to be taken into account as well, in order to make sure that their needs are addressed by proper communication.

- Decisions and procedures that have a societal effect, such as the ones about decommissioning of nuclear installations, need to have communication and public participation as a formal part of early planning, in order to be more legitimate and effective.

- More attention needs to be paid into ensuring equal and balanced stakeholder and/or public participation, both in the recruitment, as well as in the deliberating/discussion part.

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